Terra Literature Review

An Overview of Research in Earthen Architecture Conservation

Edited by
Erica Avrami, Hubert Guillaud, and Mary Hardy

The Getty Conservation Institute

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The Getty Conservation Institute works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, model field projects, and the dissemination of the results of both its own work and the work of others in the field. In all its endeavors, the GCI focuses on the creation and delivery of knowledge that will benefit the professionals and organizations responsible for the conservation of the world's cultural heritage.

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Foreword

By Jeanne Marie Teutonico

Our earthen architectural heritage is profoundly rich and complex. A ubiquitous form of construction, structures made from earth appear in the oldest archaeological sites as well as in modern building, from large complexes and historic centers to individual structures and decorated surfaces. At microscopic and macroscopic levels, as well as on physical and social planes, earthen architecture is endlessly varied and thus engages a range of disciplines in the study, research, and practice associated with its conservation.

The field of earthen architecture has grown tremendously over the last few decades. This development is reflected in a series of international conferences that have taken place around the globe—the first in 1972 in Iran and the most recent in 2008 in Mali. With each conference, participant numbers have increased, along with the diversity of attendees. Academics, scientists, professionals, and practitioners, united by their interest in earthen architecture, now convene every few years to discuss chemistry, soil science, seismology, hydrology, structural engineering, archaeology, sociology, sustainability, and more, as they pertain to our earthen architectural heritage.

As the exchange of ideas within the field has expanded, so too have opportunities for collaboration. In 1994 the Getty Conservation Institute joined forces with the Gaia Project (a partnership of CRATerre-EAG and ICCROM) to promote the conservation of earthen architecture through the first Pan-American course on the subject. Three years later, capitalizing on their independent and shared experiences in earthen architecture education, research, and field projects, the three institutions formed Project Terra.

Among the aims of this collaboration were enhancing research and building the body of knowledge related to earthen architecture. Toward this end, the Terra partners undertook the Earthen Architecture Research Survey in 1998, as a follow-up to the Gaia Research Index of 1989. The survey polled scientists and practitioners about perceived research needs and sought to identify current lab and field initiatives. The survey also served as the basis for a six-week online discussion among colleagues worldwide, which in turn led to a research workshop at the Terra 2000 conference in Torquay, England. The workshop assembled eighteen scientists, engineers, architects, and conservators who endeavored to translate this series of initiatives into a comprehensive research agenda (available at http://www.getty.edu/conservation/publications/pdf_publications/terrasummary.pdf).

During this period, Hubert Guillaud of CRATerre-EAG initiated a review of the earthen architecture literature of the past fifteen to twenty years, in order to identify trends and gaps in research. His work served as the foundation for this *Terra Literature Review,* which compiles thirteen essays on different topics germane to earthen architecture research. The seven authors come to the inquiry from disciplines as diverse as chemistry, mineralogy, engineering, architecture, and mural conservation. Each introduces the specialized bibliography of his or her particular field, mining its texts and technical publications to provide an overview of the body of literature and to outline recent trends in research. The *Terra Literature Review* is designed as a supplement to the Terra Bibliography, an online resource focused on earthen architecture and its conservation available through the Getty Web site at http://gcibibs.getty.edu/asp/.

The purposes of the bibliography and the literature review are multifold. While designed to make the body of earthen architecture literature more accessible, they also aim to support research and training and to facilitate interdisciplinary communication and collaboration. It is our hope that these publications prove useful resources for students, researchers, and practitioners, as well as effective catalysts for continued development of the field.

Though the Project Terra partnership culminated in 2006, its long-term initiatives and goals have continued under the programs of the individual member institutions. The Getty Conservation Institute continues to support the field of earthen architecture as it matures from a special-interest topic into a distinct discipline and science through a vigorous program that includes laboratory research, field projects, training, conferences, and publications focused on the conservation of earthen architecture, including this *Terra Literature Review*.

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Introduction

By Erica Avrami and Hubert Guillaud

Since the first international conference on earthen architecture conservation more than thirty years ago, the field has grown exponentially. Converging interests in sustainable architecture and in earthen heritage are charting new territory. Conservation efforts aim not only to protect earthen vestiges but to preserve the viability of designing and building with earth. At this intersection of new construction and conservation, there is a great potential for reinforcing links between the built environment and its social and natural contexts, between sustainability and development.

While earth is not a prevalent building material in most industrialized countries, the United States Department of Energy estimates that over half of the world's population lives in a house constructed of unbaked earth (including adobe, rammed earth, wattle and daub, and so on). It is primarily a vernacular form of construction—meaning built without the input of a design professional and by use of local resources. Lying outside the trajectory of Greco-Roman centered architectural history, these vernacular forms and traditions are not well represented in university curricula. Building codes in many countries prohibit construction in earth, and the lack of university- and industry-driven research and development precludes standardization and improvement of earthen materials and techniques.

These conditions have posed a great number of challenges for the earthen architecture field. There is little support for scientific research, both basic and applied, that relates specifically to the technological and cultural aspects of building with and conserving earth. Much of the research undertaken to date has been empirical testing related to the efficacy of treatments. Research from ancillary fields has offered some insights, but it often cannot be directly transferred to earthen construction or to historic earthen materials. Research related directly to earthen architecture conservation thus remains somewhat disparate, lacking the focus and resources that could be provided by a community of investigators that is better connected and more fully developed.

Though daunting at times, these challenges have prompted a fair amount of synergy within the community of practitioners working with earth. The series of international conferences on earthen architecture conservation—now totaling ten—has taken a broad view, encompassing technical research, field practice, heritage management, and new design. The conference proceedings constitute the primary venue for publishing studies on the preservation of earthen heritage. However, as Anne Oliver notes, conference publications have inherent drawbacks. Often only the abstracts are submitted to the selection committee, and the subsequent papers are, by and large, not subject to peer review. This lack of review, combined with limitations on text, results in a range of information that varies dramatically in quality and quantity. Because most studies are driven by practice, emphasis is often on sites and their conservation, as opposed to research issues that cut across the field. In the end, this significant body of conference literature provides important insights into experiences and advances in earthen architecture conservation, but it has not propagated the kind of in-depth scientific research that is needed by the field, nor has it fostered the necessary dialogue between practitioners and scientists.

This volume represents a multifaceted effort to delve beyond the core of conference proceedings and to review the broad range of studies that inform earthen architecture conservation. The aim of this effort has been to analyze strengths and weaknesses in the body of research literature, evaluate directions on which recent research has focused, and identify gaps in knowledge, so as to inform and encourage future research that is responsive to the needs of the field. Focusing on publications of the past twenty years, Hubert Guillaud of CRATerre-EAG (the International Centre for Earth Construction–School of Architecture of Grenoble) undertook an initial review of nearly thirteen hundred texts; this review provided a general lens on research areas and yielded three major themes: understanding earthen building materials, assessing earthen architecture, and conserving earthen heritage. A group of scientists, engineers, architects, and conservators then took on specific topics within these themes for further review.

The reviews themselves range in scope and function. In many cases, the published literature related to a specific topic in earthen architecture conservation is quite limited, so the reviewer has provided a synopsis of relevant research and its potential application to earthen heritage. In other instances, a substantial body of research indicated clear trends and gaps, and a traditional review of the literature has been presented.

In the section entitled "Understanding Earthen Building Materials," Bruce Velde and Hubert Guillaud address issues related to the properties and behavior of earthen materials and their constituents. Within the realm of earthen architecture and its conservation, little research has focused on these fundamental dynamics. Thus, Velde provides a summary of geochemical research and raises issues germane to earthen construction. Guillaud addresses the identification and characterization of earthen materials, which have been fairly well established with regard to new construction, and he identifies means of further developing research and translating it to earthen heritage.

In the section "Assessing Earthen Architecture," Claudia N. Cancino, Leslie Rainer, Brian V. Ridout, and Frederick A. Webster explore a range of topics related to the pathology and deterioration of earthen structures, as well as to the evaluation of their condition. Cancino looks to the heritage recording and documentation field and how it has been brought to bear on diagnosing earthen sites and buildings, and she identifies research on methods that would benefit the field. Rainer reviews the published research on earthen architecture pathology and deterioration and finds some synergy regarding the factors of decay, but she also notes a dearth of information on deterioration processes and their manifestations in particular materials and contexts. Ridout examines the relatively extensive literature on moisture monitoring and its application to earthen architecture. Webster provides an overview of literature related to assessing seismic damage in earthen structures, and he segues into conservation issues with a discussion of research on the development of seismic interventions.

In "Conserving Earthen Heritage," Anne Oliver, Leslie Rainer, and Brian Ridout discuss research concerning the preservation of earthen sites, structures, and surfaces, as well as specific forms of intervention. Oliver covers the bulk of the literature directly related to earthen architecture conservation in sections dealing with archaeological sites, nondecorated earthen elements, and modified earthen materials. Rainer looks at the specialized issue of decorated earthen surfaces, drawing links between architectural and wall paintings conservation. Ridout brings a vast body of literature related to biocontrol to bear on earthen architecture, specifically addressing research related to wall-inhabiting organisms.

While the reviews take a variety of directions, they are consistent with and underscore an integrated and comprehensive methodology for preserving earthen heritage. Many of the authors emphasize the need to relate technical research to broader issues of context—from concerns for the environment to addressing socioeconomic development. Solving technical problems requires judicious analysis of the many factors that contribute to them. Scientific research is understood as one aspect of broader planning for heritage management and of the strategic advancement of earthen architecture.

Improved links between research in the lab and efforts in the field are suggested by many reviewers, further highlighting the need for enhanced dialogue among practitioners and scientists addressing issues related to earthen construction and conservation. A particular theme that resonates throughout is the importance of follow-up monitoring and evaluation of conservation interventions; we need to know what our long-term successes and failures are in order to learn from them.

An important, final theme that emerges is the inextricable link between conserving earthen heritage and promulgating earthen building. Much of the constructive culture of earth lies in its continued evolution as an architectural form and tradition. Forging connections between conservation and new construction remains an important task, both in research and practice.

The purpose of this publication is not to provide answers but, rather, to begin to focus on the important questions. It is hoped that this compilation provides the kind of overview that will engage others in the exploration of those questions and foster an ongoing discourse and research agenda in service to the field. We are duty bound to say that there is still much to learn, for the science of earthen architecture conservation is barely nascent, although it does show great promise. Faced with the might and beauty of this tremendous earthen heritage that we wish to conserve, it behooves us to remain modest and vigilant—to seek, to experiment, and, above all, to share our experiences.

Clay Minerals

By Bruce Velde

Clay minerals are an integral part of earthen building materials. Forming the smallest grain size portion of this material, they also have specific mineralogical and physical properties that make them different from other common natural minerals. For this reason it is important to look further into their specific mineralogical character and their geologic origin.

This text provides a very brief overview of the critical properties of clay minerals in their interaction in earthen materials.[1] This is the most important aspect of clay mineralogy and the understanding of clays in nature. The chemical, internal structure of a clay mineral makes for very specific characteristics of chemical reactivity. The small size and specific crystal shape give other properties, which are more physical. Both factors contribute to an interaction of the clays with their environment that makes them important elements in interactions concerning the biosphere. Clays are at the same time physically and chemically active. They combine with water to make pastes, slurries, and suspensions by attracting water molecules to change their effective physical particle size. Clays take various chemical substances (ions or molecules) onto their surfaces or into the inner parts of their structure, becoming agents of transfer or transformation.

Physical Properties of Clay Minerals That Are Most Important for Earthen Materials

Particles and Shapes

Clays are fine-grained minerals with particle diameters of < 2 μm (10^{-6} m, 0.002 mm). This definition of a clay mineral was given in the nineteenth century to materials beyond the resolution of the optical microscope. Microscopists and mineralogists in those times saw that individual particles existed in the submicroscopic range, but they could not identify them in a systematic manner, as was done for minerals of larger size, using their specific optical properties. Thus the designation *clay minerals* came into use for submicroscopic and crystalline material. As it turns out, most of the silicate minerals of this grain size found in nature have some very special mineralogical characteristics in common, and hence, a posteriori, the choice of this name for a mineral group has, in fact, proved very useful. However, it should be remembered that not all mineral grains in nature in the < 2 μm range are of the same mineral type. Nonclay minerals, such as quartz, carbonates, and metal oxides, most often can form 10%–20% or more of a clay-size assemblage in nature.

Chemical analyses were nevertheless made of clay mineral substances of fine grain size in the nineteenth century, most often with good results. However, the crystal structure and mineralogical family were poorly understood. This lack of understanding was mostly because of the impurities in clay aggregates—either other phases or multiphase assemblages. Slow progress was made in the early twentieth century, but the advent of reliable X-ray diffractometers allowed one to distinguish between the different mineral species found in the < 2 μm grain size fraction. Now we know much more about clay mineral X-ray diffraction (XRD) properties.

The properties of clays in earthen materials are in fact dominated by their surface properties. If the clay particles are not chemically active—i.e., charged electrically—they will behave much as other minerals of the same grain size and shape, which are rarer in nature.

Clays mineral shapes can be divided into the following particle shape groups:

[1] Thanks are given to Springer for permission to use materials modified from B. Velde and I. Druc, *Archaeological Ceramic Materials: Origin and Utilization* (Heidelberg: Springer, 1999).

- *Flakes:* sheets of equal dimension in two directions and a thickness of $\frac{1}{20}$ in the other
- *Laths:* sheets of a linear aspect, where the width is great in one direction and much less so in the other; the thickness is always much less than the other two directions
- *Needles:* two directions are similar in dimension, while the last one is much greater (of which asbestos is a rare but important example)
- *Hexagons:* where the flakes have a definite regular shape

Clays and Water

Surface Effects (Newman 1987)

Small mineral crystals have a very special effect on water molecules. Their mineral surface attracts the polar water molecules through weak charge forces (van der Waals–type bonding). The crystals are covered by several layers of water molecules that are weakly bonded to them. These layers of water do not have the same physical or chemical properties as that of bulk water. These mineral-water units change the physical properties of the aqueous solution. They "thicken" it, changing its viscosity. Thus the combination of minerals and water forms a material with a special physical state. The action of mixing small mineral particles in an aqueous solution is akin to that of mixing dust and water to make mud. Any silicate mineral, the stuff of surface geology, will attract water molecules. The mineral species such as quartz or calcite do this, as do clay minerals. The surface area compared to the grain size is the determining factor that makes clay pastes so plastic.

The small grain size of the clay crystals automatically gives them a special property, one of great surface area compared to the volume of the particle. In general, the relative surface area of a grain increases as diameter decreases. The minerals most commonly called clay minerals have the characteristic of being sheet shaped (hence the name *phyllosilicate*). This means that they have even more surface area than most minerals of the same grain size, which tend to be cubes or spheres in their fine-grained state. The ratio of thickness to length for sheet-shaped clay particles is normally near 20, which is very high. This gives a clay particle nearly three times the surface area as a cube of the same volume. Thus, no matter what its specific surface properties, the importance of the surface of a clay mineral crystal is great.

There is a difference in relative surface area for different grain shapes, such as spheres, cubes, and sheet structures. The relation between particle diameter and the ratio of surface to volume (units squared divided by units cubed) varies greatly for the different particle shapes. The sheet structure, with the same width to length but a thickness of only one-tenth its length, has a very large surface area that increases greatly as particle size (diameter) decreases.

Water Molecules inside Clay Crystals (Laudelout 1987)

Some types of clay minerals have a special property that allows them to incorporate water molecules into their structure. This water, associated with charged cations, can move in and out of the structure; in doing so, it changes the dimension of the clay particle. These minerals are called expanding or swelling clays. Other clays are called, by symmetry, nonexpanding or nonswelling clays. The incorporation of water molecules into the clay structure is quite reversible under atmospheric conditions, being directly related to the ambient water vapor pressure and temperature. In general, the more humid the air in contact with the clay, the more water can be found in between the silicate layers of the clay structures. In the tropics, for example, expanding clays will tend to be constantly hydrated, while those in deserts will only occasionally be hydrated to swelling.

Swelling clays have a basic silicate structural sheet layer that is 10 Å thick. The water introduced around a hydrated cation (usually 1^+ or 2^+ in charge) forms either a two-layer structure of 5.2 Å thickness or, under less humid conditions or higher temperatures, a layer 2.5 Å thick. Extreme hydration can produce a more ephemeral 17 Å three-layer structure. All in all, hydration can vary the volume of a clay particle by as much as 75%. Thus, if one thinks of building a house with expanding clay, it is best to be sure that it is either constantly hydrated or constantly dehydrated! Most of the absorbed and adsorbed water, associated with cations, is expelled from clays at temperatures above 110°C. Concerning earthen materials, the more swelling clay present, the more shrinkage on drying one must expect.

Mixtures of Water and Clays

The interaction of clays and water can be studied from each end of the spectrum: (1) water-clay mixtures, and (2) clay-water mixtures.

1. *Water-clay mixtures:* When clays are added to an aqueous solution, there is a gradual change in the structure of the water solution as the clay particles become more abundant. As more of the water itself is associated with the clays on surface layers, the bulk properties of the solution are modified to form what is

called a slurry (suspension of clays in water), which becomes viscous as a function of the amount of clay present. The clay suspension densifies the aqueous solution and increases its viscosity. If other molecules, organic or inorganic, are associated on the clay surfaces, the clay acts as a carrier, keeping the other molecules homogeneously dispersed in the water suspension.

2. *Clay-water mixtures:* Coming from the other end of the spectrum of physical properties, when one adds water to a clay powder, the clay picks up the water and distributes it around the particles. When relatively little water is present, and the clays are just covered with water layers, the result is a cohesive but plastic mass. The weak cohesive forces of these aggregates allow the particles to slide over one another, giving a certain plasticity to the mixture. The easy absorption of the water allows one to model the resulting plastic material.

The greater the surface area of a clay particle compared to its volume (i.e., sheet > lath > needle), the more the surface properties will be apparent in those of the clay-aqueous mixture.

Another important property of small particles is their ability to stay in suspension in water because of thermal agitation (Brownian motion). Small quantities of clay particles of < 2 μm stay in aqueous suspension for many hours because of their small size. The duration of time that they remain in suspension is augmented by a flat shape, which keeps them from falling rapidly, like a sheet of paper when taken up in the air on a windy day. The suspension of clay particles in aqueous solution tends to separate them from other minerals of the same grain size that do not have the sheet shape. The effect of particle size is demonstrated when particles of an earthen material of different sizes are placed in a beaker and stirred, and settling is allowed to occur over several seconds or minutes. This effect allows clays to be transported in aqueous suspension in preference to the other minerals of larger grain size. As a result of this effect, the aqueous suspension preferentially moves clays from one area to another (stream flow, ocean currents).

Water, Ions, and Clay Minerals: Cation Exchange Capacity (Laudelout 1987)

A very important property of clay mineral surfaces is their chemical activity and their interaction with ions in solution. In natural aqueous solutions, one almost always finds dissolved material. This material is normally composed of charged ions or, at times, of molecular species that can be attracted, with their surrounding water hydration complex, by a weakly charged surface, where they are adsorbed. This is the case for most natural materials. Clays have such a weakly charged surface, but some species, the expanding or swelling clays, have a higher, internal charge, which is open to ionic migration. The more highly charged surface then lies within the clay structure. The hydrated, charged ions are thus absorbed by the clays into internal crystallographic sites. The charge on the internal surfaces of clays is much greater than on the outer surfaces, by a factor of 25 or more! The property of adsorbing and absorbing ionic species in solution is called cation exchange capacity. This capacity is measured in terms of the total of charged ions that can be fixed onto the surfaces of clays. The measurement is made as moles of ionic charge fixed on 100 g of dry clay.

If the ions or charged molecules in solution can be attracted to the internal clay surface, there will most often be a sort of selection process operating when more than one species is present in the aqueous solution. The more, proportionally, an ion is present in solution, the more of it will be on the charged clay surface (the law of chemical mass action). However, the strength of attraction of the ions onto clay surfaces (internal or external) is not the same for all species. There is a competition or selection between different species of ions available or present in solution. Some are more strongly attracted to the clay surfaces than others. This selection effect depends upon the species of clay and its chemical constitution, as well as the affinity of the ions to remain in a free hydrated state in the aqueous solution.

The composition of the aqueous solution—i.e., the concentration of ions in solution—can affect the attraction for clay sites as well. When an ion is held on a clay (adsorbed at the surface or absorbed within the clay) and displaced because of a change in its aqueous concentration, the ion is desorbed. When the desorbed ion is replaced by another species introduced into the aqueous solution, it is exchanged, in a process known as ion exchange. For simple ionic species in solution, these relations are known as cation exchange. The normal laws of mass action are active in the exchange process: the differences or deviations from ideal, one-for-one exchange (exchange being a direct proportion of the ion available for exchange) are of great importance and have been the subject of many studies. The selectivity—that is, the preference of the clay for one dissolved species over another—is of great importance to the fate of material as it passes in contact with clays.

It should be mentioned here that not only hydrated cations in aqueous solution can be fixed onto the clay surfaces or in internal sites as exchange ions. Organic molecules are often found to be attracted as either absorbed or adsorbed species.

Crystallographic Structure of Clay Minerals (Moore and Reynolds 1997)

Clays are called phyllosilicates. This name is given because in most cases their grain shape is that of a sheet, much thinner than wide or long. This aspect has a fundamental cause. With regard to the inner structure, the bonding direction of the constituent atoms is such that the strong forces are in essentially a two-dimensional array. The stronger the bond, the more tightly the atoms are held; conversely, the weaker the bond, the more likely it will be broken. Thus, when the bonds are easily broken in only one direction, a sheet structure results. Also, when the crystals are growing, they tend to grow faster in the strongly bonded direction, and the result is the same as that for bond breaking: the extension of the crystal is essentially two dimensional. The thickness compared to width and length in phyllosilicates is often about 1 to 20.

Covalent Bonding in Layers

The ionic bonding in clays is highly covalent. Roughly half of the ions present in a clay structure are oxygen (anions), and among the cations, silicon and aluminum are the major constituents. These cations and anions form highly covalent units that are commonly interlinked into what is called a network.

When viewed on an edge, the clay mineral structure resembles a series of layers of alternating cations and anions, which are largely interlinked from layer to layer via cation-oxygen ion bonding. Where layers of silicon cations are linked to oxygen anions, the immediate geometry of the oxygens around the cation (silicon) is in the form of a tetrahedron. The alternating layers of cations form different coordination polyhedra with the linked oxygen anions. The outermost layer of cations is usually silicon dominated and a *silicon tetrahedral,* in clay mineral jargon.

Another configuration of cation coordination with oxygens is one where cations have six oxygen anions around them, giving an octahedral polygon coordination; hence, it is called an octahedral linkage and layer. Tetrahedral and octahedral cation layers alternate in clay mineral structures. Most often the oxygen anion layers are ignored in clay structure terminology, and the structure is identified by the presence of tetrahedral and octahedrally coordinated cation layers.

A clay crystal is made of varying numbers of the tetrahedral and octahedral layers coordinated to oxygen ions. The crystal is a succession of repeating sequences of the basic tetrahedral-octahedral layers. These are the basic units of the clay mineral crystal.

Repeat Distances

The tetrahedral and octahedral ionic basic units, which form sheet structures of great lateral dimension, have a given and constant thickness. This is called the fundamental repeat distance of the mineral. It is measured in angstroms. There are three basic combinations of tetrahedral-octahedral coordinated ion layers in clays that are formed by:

one tetrahedral + one octahedral layer =
7 Å unit layer, a 1:1 structure

two tetrahedral + one octahedral layer =
10 Å unit layer, a 2:1 structure

two tetrahedral + two octahedral layers =
14 Å unit layer, a 2:1+1 structure

The repeat distances are generally identified by X-ray diffraction. These layer thickness dimensions can also be seen by high-resolution transmission electron microscopy. In clay mineralogy, one frequently refers to the major mineral types by the fundamental repeat distance, such as a 10, 14, or 7 Å mineral.

Crystalline Water

Hydrogen ions are also present in all clay minerals. They are in fact cations, but they are special ones. They are associated with oxygen ions in specific parts of the mineral structure, where octahedrally coordinated ions are present. When heated, the clay yields this hydrogen in the form of water, combining with oxygens in the structure; hence it is called crystalline water. This hydrogen or crystalline water is strongly held in the structure, and heating to hundreds of degrees Celsius is required to extract it. The sites of hydrogen ions in clay structures are as follows:

- If only octahedrally coordinated cations are present, hydrogen ions are associated with the two layers of oxygens in the octahedrally coordinated cation layers.

- If the structure has two tetrahedral layers and one octahedrally coordinated layer of cations, the hydrogen is associated with only one of the oxygen layers.

When the crystalline water is expelled from the clay structure, it loses its form and becomes amorphous. This heating process is the basis of the formation of clay-based ceramic materials. Destruction of clay structures occurs at temperatures ranging from 450°C to 650°C, after heating periods of several hours. The temperatures at which this material leaves the structure can be used to identify the clay mineral.

Chemical Substitutions in the Structures: Ionic Substitution and Charge Balance

Different Layer Types

It is possible to look at the ions and charge balance in a clay mineral by either considering the cations or the anions in a given portion of the structure. For example, one can consider the tetrahedral unit either as a silicon cation surrounded by oxygens, or as four oxygen anions enclosing a silicon ion. In most chemical structural formulas for minerals, both the cation and the anion content are given. The charge on both must match.

The standard structurally linked clay units of 7, 10, and 14 Å are given as follows, in terms of the oxygen and hydrogen content:

$$7\ \text{Å} = O_5(OH)_4 = -14$$
$$10\ \text{Å} = O_{10}(OH)_2 = -22$$
$$14\ \text{Å} = O_{10}(OH)_8 = -28$$

Tetrahedra

Each cationic layer in a layer structure has a given charge per unit cell. The tetrahedral unit has a charge of 4^+ per site. It is assumed by convention that all of the tetrahedra, a majority being occupied by silicon ions, are occupied in all clay structures. Moreover, there are no hydrogen ions associated with the linked oxygen ions of the silica tetrahedra.

Octahedra

The octahedral cation sites have a total charge of 2^+ per site. In the octahedral, there are either two ions of charge 3, or three ions of charge 2, giving a total charge of 6^+. The arrangement of two ions is designated as a dioctahedral mineral, and the arrangement of three divalent ions is a trioctahedral mineral. The hydrogen ions in clays are found associated with these cations.

Ionic Substitution

As in most natural minerals, different elements can be found in the two cationic sites, tetrahedral and octahedral, described above. Such a continuous array of compositions is called *solid solution,* a term that references the gradual change in composition possible, without abrupt discontinuities or gaps.

Isocharge Substitution

If an ion of the same charge is substituted in a site, no other compensation is necessary. For example, if Mg^{2+} substitutes for Fe^{2+}, they are both divalent, and no other compensation is necessary in the structure.

Charge Imbalance Substitutions

Ionic substitution of cations with nonequivalent charges in one coordination layer of the clay structure (tetrahedral or octahedral) results in a charge imbalance that creates a charge on the layer of the clay unit. This charge imbalance attracts cations of opposite charge—hence, the cation exchange capacity described above, and the insertion of hydrated ions into the clay structures. If the charge induced by substitution is high, the cation is absorbed without hydration. Thus, there are two types of clays, those that swell (accept hydrated cations between the structural units) and those that do not, called nonswelling clays. These nonswelling clays can have an uncharged structure or a high charge structure.

Clay Mineral Classification

Swelling Clays (Low Charge on the Unit Layers), or Smectites

The property of absorbing cations and water into the clay structure defines the major classification of clay minerals: their swelling properties (expanding minerals and nonexpanding minerals) and the basic crystallographic repeat unit of the layer structures. All swelling or expanding clays have a 2:1 structure, with two tetrahedral layers and an octahedral layer. These swelling clays are called smectites.

Dioctahedral Smectite (Swelling Clay)

- *Beidellite* is an aluminous mineral with two tetrahedral layers of mostly Si ions. Al substitution is the major source of charge imbalance. The octahedral layer is composed mainly of Al ions.

- *Montmorillonite* is an aluminous mineral with the two tetrahedral layers almost exclusively occupied with Si. Charge imbalance comes from divalent ion substitutions, Fe or Mg, for trivalent Al in the octahedral site.
- *Nontronite* is a ferric mineral with minor substitution of Al in the octahedral site, and occasionally Mg ions substituting for Fe ions.

Trioctahedral Smectites (Swelling Clay)

- *Saponite* has a charge imbalance largely dominated by substitutions in the octahedral site by the introduction of divalent ions and by the presence of vacant sites that lower the positive charge balance, necessitating a compensation in the interlayer site.
- *Vermiculite* is characterized by material that comes from rather special, nonclay environments, hydrothermal alteration, and soils; swelling is low.

Nonswelling Clays (No Charge)

7 Å 1:1 Clays

- *Chamosites* are trioctahedral clay types with Mg and Fe in the octahedral.
- *Kaolinites* are dioctahedral clays containing only Al.

10 Å, 2:1 Clays

- *Pyrophyllite* has exclusively Al in the octahedral site.
- *Talc* always has near three divalent ions in the octahedral site, with a small number of trivalent ions in the octahedra and tetrahedra. Significant substitution of Fe for Mg occurs in the octahedral site.

Nonswelling Clays (High Charge)

Micas

- *Micas* have a charge imbalance between 0.8 and 1.0, and as a result, there is an interlayer ion between the layer units that strongly binds the mineral into a coherent unit of several to many 10 Å layers. These minerals are micas or mica-like minerals, and they are exclusively dioctahedral in low-temperature environments. The interlayer ion is almost exclusively K. There are no trioctahedral micas that are stable in clay mineral environments. In minerals that originate in the clay mineral surface environments, charge on the structures is always slightly less than the 1.0 per unit cell typical of a mica. Hence, these minerals should be designated as mica like, since they are not true mica structures. True micas have a different composition as far as charge is concerned, and they are also generally found in rocks that have been subjected to higher temperatures than those where clay minerals form (Velde 1985). Micas are usually of greater grain size than clay minerals, > 2 μm when they form.
- *Illite* is an aluminous 10 Å mineral with some substitution of Fe^{3+}, Mg, and Fe^{2+} in the octahedral site and some Al in the tetrahedral site, which gives rise the greatest part of the layer charge imbalance. Si content is usually less than 3.50 ions. Two tetrahedral and one octahedral layer with an interlayer ion population (K) holding the layers firmly together give a near 10 Å unit layer. This is the most common mica-like mineral found in earthen materials.
- *Glauconite-Celadonites* are more rare, Fe-bearing, low-temperature micaceous (potassic) minerals.

14 Å Chlorites: Two Octahedral + Two Tetrahedral Unit Layers, 2:1+1

These minerals are similar in composition to the 7 Å berthierines. In low-temperature environments, chlorites are strictly trioctahedral, with ditrioctahedral-type substitutions in up to half of the octahedral sites. This substitution is also found in the berthierine-serpentines (7 Å minerals). Some substitution of trivalent ions (Al^{3+}) in the tetrahedral site also occurs, which compensates a portion of the trivalent ion substitution in the octahedral site. Thus, the chlorite compositions are the result of complex, simultaneous substitutions, presenting several types of ionic substitution at the same time. The basic structure of chlorites is, in fact, similar to that of a mica or a micaceous mineral, but the interlayer site is occupied by a hydroxyl octahedral layer. Chlorites found in low-temperature environments, such as in soils and on the ocean bottom, are very rich in iron. As temperature increases, chlorites become more magnesian (Velde 1985).

Mixed Layered Minerals

The mineral types and structures described above are relatively simple. Being composed of either two-layer or three-layer units to form either 7 Å or 10 Å minerals, chlorites can be considered to be a derivative of the 10 Å structure. There is, however, a relatively large number of cases in which a single clay crystal is made up of a composite of different basic structures. Since the clays are phyllosilicates, the mixed layering occurs in the layer plane. For example, a layer of mica can be substituted for a smectite layer in a mineral. These minerals are called interlayered or mixed layered minerals, terms that refer to their composite structure, which consists of a series of different layers of compositions corresponding to mineral species. They are generally considered to be a more or less stable (or at least persistent) assemblage of different layers in crystallographic continuity. However, they often occur in geologically dynamic environments where mineral change is evident, and hence, they are often considered to be transition or intermediate phases (Velde 1985).

Not all mixed layer phases fall into in the category of intermediate minerals—some being formed in specific conditions with neither precursor nor apparent successor minerals. They do not show a gradual transition in bulk composition. However, whether or not mixed layer minerals are stable phases, they do exist, and they can be characterized by X-ray diffraction and other methods.

Mixed Layering Mineral Types

If the elements in a mixed layer mineral are repeated with regularity, the mineral is called a regular mixed layer mineral. Otherwise, the clay is an irregular mixed layer mineral. We will take the most prevalent case of two layer types, here called A and B. Mixed layer minerals are common. Most of the clay types are mixtures of mica and smectite—that is, 2:1, tetrahedral-octahedral alternances of swelling and nonswelling unit layers. Occasionally one finds kaolinite (1:1 structure) interlayered with smectite (2:1 structure).

Nonclay Minerals in Earthen Materials

Iron Oxides

The oxides of iron are not generally considered clay minerals, although they are of small grain size. However, they are not silicates, and hence are often neglected in the discussions of clay minerals. This is a great injustice to iron oxides because they are very apparent, despite their general low abundance in soils, sediments, and sedimentary rocks. The simple fact of the presence of iron oxides is that they are very strong coloring agents. These colors are quite remarkable, and they also tell us something about the chemical conditions under which the materials containing them formed. The basic colors, along with their minerals and compositions, are as follows:

red	hematite	Fe_2O_3
yellow to brown	goethite	alpha-FeOOH
orange	lepidocrocite	gamma-FeOOH
black	maghemite	FeO

Zeolites

Zeolites are frequent in some clay mineral environments. They generally indicate the existence of a high silica activity in the aqueous solutions, affecting silicate crystallization. Zeolites are not phyllosilicates, and for the most part, they have crystal sizes above the 2 μm limit given as a definition of clay minerals. However, this very brief treatment of these minerals is due to their frequent association with clays in their finer fractions.

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Geology of Clays and Earthen Materials

By Bruce Velde

This paper provides a brief description of the occurrence of clays in nature, especially those found at the surface of the earth and, thus, most likely to be used for earthen building materials.[1] Such occurrences concern the geology of clays: the geological processes that lead to the creation of clays, the transformation of clays, and the destruction of clays in the different geological environments. Clays, as is the case for most materials on earth, are ephemeral. They have a life span that is governed by their geologic history. Clays occur under a limited range of conditions in geological space (time and temperature, essentially depth). They are found at the surface of the earth. Their origin is, for the most part, initiated in the weathering environment (rock-atmosphere interface), though some clays form at the water-sediment interface (deep sea or lake bottom). A few clays form as a result of the interaction of aqueous solutions and rocks at some depth in a sedimentary pile or in the late stages of magmatic cooling (hydrothermal alteration). This last occurrence is not great in extent, but it is very important to geologists, as they have often been called upon to aid human activity in the form of economic deposits used in ceramics and other industries.

Why Clays Form (Velde and Druc 1999, 59–73)

Most clays are the result of interaction between aqueous solutions and rocks. The dissolution and recrystallization process that occurs at this encounter is that of clay mineral origin and transformation. Clays are not stable in anhydrous environments. The proportion of water to that of the solids (rock) that interact determines the rate of reaction, the type of chemical reaction, and, in the end, the type of clay mineral formed. When large amounts of water are present, the solids in the rock tend to be very unstable and, for the most part, they dissolve. Dissolution is the first step of most water-rock interactions. The greater the renewal of the water input (rain or fluid circulation), the more dissolution will occur. As the ratio of water to rock approaches 1, the reactions are more and more dominated by incongruent dissolution, in which certain elements go into solution and others remain in the solid state left in the skeleton of the altered rock. The new solids are generally clay minerals; they are hydrated (having interacted with water), and they have a special physical structure that is very different from that of the preexisting minerals in the rocks that reacted with the aqueous solution. Because of their hydration, they have a greater volume than the previous minerals. The initial stages of alteration and those that follow include significant dissolution of rock material; thus, the formation of clays results in an aggregate of lower density than that of the initial rock. Voids are usually produced in the alteration or clay-forming process during water-rock interaction. The proportion of voids produced is a function of the relative amounts of water and rock that interact.

Where Clays Form

The different clay mineral environments are related in space, at or near the surface of the earth. The clay environment is limited to a certain range of temperature, and it is also limited in time. The stability of most clays is, in fact, only attained at the very surface of the earth, in approximately the first several hundred meters of depth in the earth's crust. When temperatures exceed more than 50°C–80°C, the clays are unstable, and they begin to change into other minerals—either into other clay minerals or into different mineral structures such as micas and feldspars. Long periods of time can effect change in the mineralogy of the clays them-

[1] Thanks are given to Springer for permission to use materials modified from B. Velde, ed., *Origin and Mineralogy of Clays: Clays and the Environment* (Berlin: Springer, 1995) and B. Velde and I. Druc, *Archaeological Ceramic Materials: Origin and Utilization* (Berlin: Springer, 1999).

selves. If temperatures are of lesser duration, for periods of days or years, the temperatures needed for clay formation can reach several hundreds of degrees centigrade.

Clay Formation: The Chemical Necessity

The origin of clay minerals is found in the interaction of rocks (silicate minerals) and water. This indicates that the clays are hydrous—and more so than the minerals in most rocks. The overall reaction of

$$\text{rock} + \text{water} \rightarrow \text{clay} \qquad (1)$$

is a reasonable starting point to describe the origin of clay minerals. However, things are more complex than that. The mechanism by which water "hydrates" silicate minerals is hydrogen exchange. Most clay minerals in fact contain molecules (OH) that have a specific role in the mineral structure. The only difference between, for example, a potassium ion (K^+) and a hydrogen ion (H^+) contained in water is that the hydrogen ion can be expelled from a mineral structure at lower temperatures than the potassium ion. In fact, the potassium ion will be incorporated into another mineral instead of leaving the solid phase upon destruction of the clay mineral, whereas the hydrogen ion tends to form a gas (combining with oxygen to form water), which leaves the clay when a high enough temperature is reached (usually between 400°C and 600°C in clay minerals). In a very general way, one can describe the thermal stability of hydrogen-containing minerals such as clays as

$$\text{clay} + \text{heat} \rightarrow \text{rock} + \text{water} \qquad (2)$$

which is roughly the reverse process of clay formation (1).

The geologic causes of clay mineral genesis are found in temperature change and in chemical change. The major environments of clay formation and accumulation in nature are as follows: surface interaction (weathering) dominated by chemical change; transportation and accumulation (sedimentation); and deposition and burial (sedimentary rock formation).

Weathering (Righi and Meunier 1995; Brady and Weil 2002)

Segregation of Elements by Weathering

Initially it is necessary to go back to rocks. Rocks are hard and compact and have their origin generally somewhere well below the surface of the earth—i.e., below the interface of air, water, and rock. They are hard and compact because they have been compressed by the weight of sediments or other rocks at some depth as they have been buried. This increase in pressure is accompanied by higher temperature with depth in the earth's crust. When taken out of their natural habitat (high pressure and temperature), rocks are unstable in wet conditions. Rainwater, when combined with atmospheric carbon dioxide (CO_2), becomes slightly acidic, containing an excess of hydrogen (H^+) ions, and this attacks the rocks. Hydrogen is exchanged for cations in the minerals, and this phenomenon is called weathering when it occurs at the surface of the earth. The end result of surface alteration processes is the production of clay minerals and oxides, which form the basis of mud, and ion-charged water. Unreacted material forms sand.

The interaction of acidic water and rocks in weathering involves segregation of the major elements into new minerals: clays, oxides, and soluble elements. The cation elements that are found in clays of weathering origin are silicon (Si), aluminum (Al), hydrogen (H), and some iron (Fe) and magnesium (Mg). One also finds some potassium (K) permanently fixed in the mineral. The oxides are mostly iron (Fe) forms.

The calcium (Ca), sodium (Na), and, to a slightly lesser extent, magnesium (Mg) and potassium (K) are taken into solution. The fate of most of the material in solution is eventually to find its way into the ocean, where a large portion of the cations are used by animals to make their carbonate-rich shells (Ca and some Mg). These shells are the basis for a type of sedimentary rock, carbonate, which is very common. Sodium remains in the sea, giving it its salty character.

During the interaction of rainwater and rocks to form clays and oxides, some of the grains in the rocks are not entirely reacted with the rain. These are part of the alteration product; they are in granular form and are sandy or gritty in texture. Weathering thus produces two of the major components of earthen building materials: clays and sand. The proportion of these elements in a soil profile varies as a function of depth.

The Structure of a Weathering Profile

Soils are probably the major source for earthen materials used in housing and small-dwelling construction. Hence, it is necessary to look at the details of soils. Soil formation is dependent on dynamic processes. The variables of soil formation are climate (rainfall and temperature), source rock (mineralogy of the initial substrate involved), and geomorphology, which is considered to be dominated by slope. In cold, steep-sloped mountains, there is little soil, while on flat continents in hot climates, the soils are very deep. Time is another factor in explaining the thickness and development of soils. The older the soil, the deeper it will be. All of these factors are related to the type of vegetation that is present, and this also has a very strong influence on the soils developed. Hence, the soil one finds in a given spot is due to several, often interrelated factors.

Parts of an Alteration Profile

The initial stages of soil formation are found at the base of the soil profile where the bedrock begins to be transformed into what is called saprock. This transformation is gradual, affecting selected mineral grains in a multi-mineral assemblage, as is the case for most rocks. Each mineral grain has several characteristics that are related to its transformation into clay minerals. Some grains in the same rock are very easily transformed, whereas others remain little affected. As a general rule, the higher the alkaline earth content (Ca, Mg in the case of silicate minerals), the more unstable a mineral will be. Also, the presence of divalent iron (Fe^{2+}) is a factor of chemical instability. Iron has a strong tendency to be oxidized to a trivalent state (Fe^{3+}) in the surface environment. When it changes valence, the electronic balance of the initial mineral is changed, and as a result this mineral becomes unstable, changing to another or other minerals. Therefore, rocks containing alkaline earth and iron-bearing minerals will weather or be altered very rapidly. These initial processes occur in the saprock sector of a soil profile. As further alteration occurs, almost all of the original minerals are changed to some extent, except for the most chemically resistant. In this part of the profile, the old rock identity is mostly lost, and only traces of the original minerals remain. This is the saprolite part of an alteration profile.

In the soil portion of an alteration profile, one finds only clay minerals and some sand grains that are resistant to weathering. No trace of the old rock structure is left. At the top of this part of the alteration profile, one finds the root mass of the plants growing in the clay-rich portion of the alteration profile. The soil portion of the alteration profile is usually divided into the upper, organic-rich horizon (A), a clay-enriched horizon (B), and the underlying source material, which is generally the saprolite. The A horizon is defined by organic activity, and the B horizon by the accumulation of clays by fluid flow through the A horizon.

Variations in Weathering Profiles (Velde 1992)

Development of a soil is dependent upon where it is formed; this fact is due to several factors:

1. *Water, time, and chemistry:* In weathering phenomena, there are several guiding principles one can use to follow or predict which minerals will be formed in a given setting. The types of clay minerals formed are dependent upon the ratio of water to rock involved in the process and the type of rock (its chemistry) involved. In initial stages of alteration, at the initial contact between rock and water, the rock has a strong influence on the clay mineral compositions and the species present. Since rocks are chemically variable, the clay assemblages are more varied in this environment. As water-to-rock ratios change and water is more abundant, the rainwater becomes more dominant. Since the chemical variability of rainwater is very limited, the clay mineral assemblages become very limited. However, if the chemical forces are overwhelming, such as in the wet tropics, the soils will yield all the same minerals regardless of the parent material at the base.

   In the course of interaction between solids and liquids as rainwater, the aqueous phase is initially unsaturated with respect to the elements or ions present in the solids. The first interaction is one of dissolution of the solids to come to an initial equilibrium. This dissolution selectively takes from the solids the monovalent and divalent ions (K^+, Na^+, Ca^{2+}, Mg^{2+}), leaving behind the trivalent (Al^{3+}) and quadrivalent ions (Si^{4+}). This is the famous hydrogen-for-cation exchange step, or hydrolysis, of the solids. If the rainwater supply is renewed frequently, the overall effect is to take out all of the potassium, sodium, calcium, and magnesium from the soil-rock. The resulting solid material tends to be of the same chemical composition and, hence, of the same clay mineralogy. The result is an accumulation of hydroxyoxides and oxides in the solids. If the supply of unsaturated rainwater is limited, there is time for the solutions to saturate themselves with the soluble ions, with some left over to enter into the soil clay minerals. Under these circumstances, the clay minerals become more varied and complex. As the pressure of dissolution is lessened, the variety and complexity of the clays increase.

Thus, these three factors (water supply, time, and chemistry of the rocks or soils concerned) are dominant in the formation of soil clay minerals and soils themselves.

2. *The effect of climate:* Overall, climate, as it affects weathering, can be measured in terms of rainfall and temperature. The more often it rains, the more water is present in the pores and cracks of a rock or soil, and the less time it has to become saturated with the elements in the solids. The hotter the climate, the faster chemical reaction proceeds, and the more intense the alteration. Tropical, wet climate is found at high-intensity conditions where the variety of clays is small; desert, mountain, or arctic climates are found at low-intensity conditions where the interaction is so small that few clay phases are formed, and the interaction is dominated by physical processes. Temperate climates—in which rain is relatively abundant and temperature is moderate—produce the greatest variety of clay minerals in the alteration of rocks and soils.
3. *The effect of slope or drainage:* Slope and drainage are similar to the climate effect, except that they operate under the same conditions of climate. The higher the slope, the less time the rainwater resides in the soil or at the interface of rock alteration. This water is renewed frequently and has little time to become saturated with the soluble elements in the solids. The result is that high slopes give weathering intensity results similar to those of intense tropical weathering. However, if the slope is extremely high, the water-rock interaction is so minor that no alteration occurs, and one is in the situation of desert or arctic soils, where the only forces are physical; such forces break up the rock without changing the mineral composition.

   One important aspect of the effect of slope is the displacement of material through erosion. Combined with the effect of running water, gravity has a tendency to displace soil materials to the bottom of slopes. This circumstance has the effect of mixing materials that have been produced on the upper portions of a slope with those formed in lower areas of the slope. Hence, some material that has been little affected by chemical alteration is mixed with material that has reacted greatly with altering rainwater solutions. Probably as much as the chemical effect, this mixing contributes to the heterogeneity of clay assemblages in soils. High slopes give more erosion, and this takes away the clays formed chemically, leaving a new surface open to attack by abundant rainwater.

   Weathering profile thickness is affected by slope. On mountainsides, the water, though it may be abundant, will tend to run off rapidly, and hence the soil is not very thick there. Lower, more gentle slopes allow more water-rock interaction, and soil profiles become thicker and richer in clay. Hence, topography is a factor in the production of clay minerals by weathering. Weathering profiles that are very old will be thick. The action of alteration has much time to accomplish the production of clay minerals in old weathering profiles. Soils developed on old, flat, and stable areas, such as western Africa, tend to be very deep and rich in clay, reaching tens of meters in depth.

From Rocks to Soils to Sediments and Back to Rocks (Hillier 1995; Velde 1995; Weaver 1989)

The weathering origin of clays, or the new minerals formed at the earth's surface, is by chemical exchange. This chemical process is then integrated into the general scheme of geologic interaction that is physical interaction—mountain building and erosion, processes that give rise to the common features we see at the earth's surface. Rivers and lakes, floodplains, and beaches are all important sources of geological interactions that create an accumulation of earthen materials.

Water Flow and Sedimentation

If one takes the product of weathering—that is, soil—and puts it into a beaker or glass, then stirs it up, a mechanical sorting is effected. The lightest and, more importantly, the smallest grains settle more slowly. As most silicates have about the same density (around 2.5 times that of water), grain size is a very important factor in settling. The smaller the grain, the more friction is effected on its surface as it falls through the water. This action is basically controlled by the ratio of the surface of the grain to its volume. As clays are the smallest materials with regard to grain size, they tend to stay afloat longer and can be separated from bigger grains.

If one pours the beaker, the clays are separated from the sand and gravel. When the remaining material is stirred again and allowed to settle less, one can extract the sand fraction from the gravel, and so forth. This is a fundamental process in nature. As hills are eroded and valleys created, the materials in a soil profile, from top to bottom, are exposed to water transport. The fine-grained materials, clays as well as sands and gravel, are transported by streams and rivers toward the sea. The destination of all flowing water is, of course, the sea, even though most does not make it there. As one moves from higher slopes to flat terrain, the grain size of deposits decreases. Along the ocean, one finds fine beach sands, and on the ocean bottom, clay minerals. The same is true to a lesser extent in lakes, where water moves slowly and there is time for the fine-grained materials to find their way to the bottom of the body of water.

In the zones of river transportation on terrain of moderate slope, there are several possible types of deposits that will be found near one another. In such areas, builders using earthen materials can choose their materials from among those in a small geographic area. Along rivers one can find mixtures of fine sand and clay, especially on floodplains along flat-lying rivers. Those rivers that wind their way through the countryside will give mixed deposits of clay and sand. Often in one spot there will be a concentration of sand, while in another nearby area, there will be a concentration of clay. In the bed of the river, one finds more sandy deposits. The dynamics of transportation and the origin of earthen materials in a typical countryside are demonstrated in a hypothetical situation, in which a large river flows through a slightly hilly terrain. The river cuts into the underlying bedrock, exposing a clay-rich sedimentary layer on one of the sides of the valley the river has carved. The soil formed from this material, as well as that from another type of rock on the other side, is eroded or carried to the river bottom by gravity and rainwater action. Along the riverbed and bank, one finds deposits of earthen materials (rich in clay and sand) that are deposited during high water or flood stages. These will be more fine grained than in the river bottom. Next to the river, the higher-energy deposits, which are more sandy, occur. In this situation, one can find several sources of earthen materials readily at hand: sedimentary rocks, soils, river floodplain sediments, and river bottom sediments. Each will have a different grain size distribution, more fines, and more sand and will be adapted to different uses.

Wind Transport

A special type of transport and deposition is the wind. This type of transport is mostly concerned with fine material above clay size (greater than 0.002 mm). Most people know about sand dunes, large accumulations of sand along seacoasts or in desert basins. These materials are largely moved and deposited by wind. A second type of deposition is through wind acting on glacial outwash plains. During the time of continental glaciation, large amounts of fine materials were deposited on the edges of the glaciers by streams. This material was in turn swept around in great windstorms, and it accumulated farther from the glacier's edge. These outwash plains and silt deposits (silt is a fine-grained sand that is carried farther than sand because of its smaller size) typically cover hundreds of miles from the glacial edge. They could subsequently be concentrated on the floodplains of rivers. The most striking examples of this type of deposit (called *loess*) are found in China. However, in large portions of North America (especially in the Midwest United States) and in northern Europe, loess deposits are very frequently present. The loess layers vary from tens of centimeters to meters in thickness. This fine-grained material—in fact, a mixture of silt and clay—can be readily used in the production of earthen structures.

Burial of Sediments

As sediments are deposited in basins or on the edges of oceans, they tend to be buried by other sediments. This process implies that the floor or basement on which the sediments are deposited descends as new sediments are added onto them. This is roughly true, though sometimes sedimentary basins get filled and sedimentation stops, and sometimes the basement subsides faster than the sediments can fill the basin. The filling basin is the most commonly evoked in geology, where there are just enough sediments to keep up with the subsidence of the bottom of the basin.

A given layer sedimented at a given time in geologic history will be buried progressively. Thus it goes deeper into the earth, and, as is the case, the ambient temperature increases. The ambient pressure also increases. As sediments are piled on top, pressure tends to favor the more dense phases (silicates have a density 2.5 times that of water), and hence the water of sedimentation is expelled. The sediments become drier. Upon sedimentation—i.e., deposition on the floor of the ocean—clay-rich materials have a free water content of 80%. That is to say that there are about 80% holes in the sediment. As this sediment is buried, its free water content decreases, the holes or pores decrease, and they become about 15% of the sediment at depths of 3 km. This process changes the physical properties of the sediment.

Also, as burial is greater, temperature increases, and this effects change in the minerals present. Temperature is the motor of mineralogical change. When enough thermal energy is added to the sediment, its mineralogy will change. The clays produced at the surface in the soils will no longer be stable, and they will be replaced by others. The old ones recrystallize to become others that are more stable at higher temperatures. A change in form and mineralogical identity occurs. This is the process of metamorphism. As the minerals change and water is expelled, the structure of the rock becomes more dense, and the increasing pressure effects a densification of the sediment. The soft, deformable sediment becomes a hard rock.

Sedimentary Rocks

Sedimentary rocks are composed of soil-derived materials, rich in clays and/or sands, or else they are derived from the dissolved species of elements brought by rivers to the sea, where they are transformed into carbonates, essentially through the action of shell animal life. The three main groups of sedimentary rocks are carbonates, sandstones, and shales, the last being formed from clay materials. As might be expected, the carbonates will redissolve when subjected to acid rainwater interaction. Their contribution to soils is minimal. Soils developed on carbonates tend to be clay rich, formed from the clays included in the initial carbonate rock.

Shales, the result of consolidation and minor change in the soil-derived sedimentary material, are, of course, rather resistant to chemical weathering because the minerals found in them are nearly always those stable at the surface under weathering conditions. The difference between a sedimentary rock clay mineral and one found in the soil developed on it is not great, and hence they tend to resemble each other. Shales develop thick, clay-rich soils. Shales can often be used directly as earthen materials. Sands and sandstones are the most resistant to chemical attack under weathering conditions, because they are formed by the concentration of the most chemically resistant mineral—quartz. This mineral remains largely intact and is recycled many times in the geologic landscape.

In general, the less change a sediment has undergone through the actions of sedimentation and burial, the less it will react with the chemical environment of weathering.

Metamorphic Rocks

These rock types are all of generally high cohesion—that is, they are hard and dense—and physically they behave largely like volcanic or plutonic magmatic rocks. Metamorphic rocks are those that have been transformed, metamorphosed, from others by heat and pressure. Initially, metamorphic rocks were either sedimentary or magmatic materials.

Characteristics of Materials Suitable for Earthen Structures

For the moment we will consider two types of material: clays and nonclays. One, clay, is a term related to grain size (< 2 μm, 0.002 mm or 10^{-6} m), and it also designates a type of mineral with a peculiar grain shape, one like a sheet of paper. Nonclays are of grain sizes greater than clays. The nonclay materials are usually divided into grain size categories of silt (2–50 μm in diameter) and sand (50 μm to 2 mm in diameter). These two size categories are usually of nonclay material (sheet silicates), and hence they have a relatively small attraction for water because of their relatively small surface area compared to their volume. For the most part, these materials are nonplastic. The various combinations of these grain size categories have given rise to the classification of earthen materials. Unfortunately, there are two such classifications, one used by people studying sediments (sedimentologists) and the other used by people dealing with soils.

The origin of earthen materials, then, involves the chemical origin of clay minerals, weathering. It also involves the transportation of weathering products that produces different types of concentrations of the more or less fine-grained material. These concentrations are found in different types of sites—riverbeds, floodplains, beaches, and lake and ocean bottoms. Some of the material that can be considered to be earthen material is, in fact, a sediment or deposit that has been subjected to mild burial conditions, those of poorly consolidated sedimentary rocks. The origin of earthen materials is, thus, not only related to chemical effects (weathering) but also to the transportation of these materials.

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Formation of Earthen Materials

By Bruce Velde

The earthen materials used in construction are quite diverse, because of the variations of local resources and building techniques. This paper does not attempt to address the full range of materials and typologies. Rather, it provides an introduction to some general principles that inform the relationship between building materials and their formation.

Methods of Forming Earthen Materials

If one considers the possible methods of producing materials for building that support significant forces—i.e., structural elements[1]—there are essentially two processes:

1. Mixing the earth with water to a liquid state, forming the desired shape in a mold, and letting the water escape by evaporation. This is, roughly speaking, the adobe technique.
2. Slightly dampening the earth to a desired state in which the material is composed of three materials (solids, water, and air), with the last two occurring in pores, or "empty," spaces. The preparation is placed into a mold the size of the final desired object, and a high-energy impact is applied to compact the earth. This is the pisé, or rammed earth, technique.

The two materials, rammed earth and adobe, are diametrically opposed with regard to the physical methods used to achieve the final state and volume of the building material. In the case of adobe, the loss of water shrinks the material into the final shape. Volume loss can often reach 20%. Shrinkage must occur toward the center of the object in the mold, so that few cracks are formed. The solid grains approach one another by mutual attraction forces. The hardened, dry material should have a high crushing strength. The individual elements produced by the process are relatively small in size and stacked, to produce the eventual building element, such as a wall.

The rammed earth method takes the opposite approach, by expelling the water by compaction pressure and having the constituent grains approach one another by force. The building element is near the final size of the object to be produced, such as a wall. Here the desired mechanical strength is obtained by dynamic force and not by natural attraction of the individual constituents.

With such different approaches to building, it follows that constituent materials in the rammed earth and adobe methods will be different, along with grain size and other characteristics. One would expect grain sizes, types of constituents, and so forth to be different. However, at present, there is no real consensus as to which characteristics of earthen building materials most influence performance (see "Characterization of Earthen Materials," p. 21). What this discussion attempts to do is to explore some of the varying characteristics of earthen materials from the limited perspective of how they were formed, in the hopes of informing continued discussion and research.

Drying, or the Adobe Method

This method employs the shrinking characteristics of clay and earthen materials as the principal agent of formation and stability of the building product. The natural tendency of clays is to form a compact and resistant mass upon drying. This is not the case for nonclay minerals. Most likely, the difference between clay and nonclay grains is due to the shape: clays have a flat shape with large, flat surfaces that can be attracted to one another on drying by electrostatic forces, once the water layers naturally attracted to the clays have left the system. In nonclay materials, the grains are shaped in a more irregular manner, where grain-to-grain

[1] The formation of nonstructural elements (i.e., non-load-bearing elements, such as wattle filling in walls) is not considered here.

contact surface area is reduced, and the contact cohesion by electrostatic forces is much lower (Prost et al. 1998).

Adobe materials can nevertheless have quite variable clay content (Coffman et al. 1990). Thus, ideal conditions are often not met, and the necessity of adaptation of local materials is seen to come into play. In order to overcome the inadaptability of local resources, other materials are often added to the earth material, such as vegetal matter (Miller 1934; Orazi 1995) or calcite and perhaps lime (Jerome 1993; Austin 1990). It has been noted that similar materials coming from the same area that are used for rammed earth or adobe constructions have different grain size distributions (Ranocchiai, Fratini, and Manganelli del Fá 1995). The specific limits of proportions of clay and nonclay materials used in adobe practice seem, for the moment, to be unknown.

One important requirement, however, is that the materials dry into a homogeneous, compact mass without cracks forming within it. This principle is simple enough in theory and must be respected rigorously in practice. In the formation of adobe bricks, the proportions of the clay minerals and the specific species of clays (swelling or nonswelling), among other factors, will determine the properties of the final product. For example, the wind-derived loess deposits of China would seem to be well suited in that they contain little swelling clay, whereas the nice black earth of the Midwestern plains in the United States, derived from loess but formed under grass vegetation, contains much swelling clay and would perhaps be a poor candidate. In addition, the shrinkage of the clay masses can be significantly influenced by the common practice of adding other materials—such as vegetal matter, lime, or calcite—which may serve as binders. However, before such generalizations can be drawn, more precise investigations must be made into the types of material used and their mineral plus organic material content.

Compaction

Static Compaction (Craig 1992, 248–99)

Compaction is generally studied in the laboratory in a simple oedometric system, where a sample is held in a rigid tube and pressure is applied uniaxially, perpendicular to the tube. The system has infinite constraints laterally to prevent deformation and has a deviator of variable force vertically. Most tests are carried out in the water-saturated state, in order to avoid problems of heterogeneous rigidity due to the structure or resistance of dried clay materials. These conditions are, of course, not those of earthen building materials, and hence there are significant challenges in applying such information to the studies at hand. Water saturation is a reference state in laboratory compaction tests. The water in the sample is allowed to drain from either end of the sample under pressure, so that the pore pressure (internal hydrostatic pressure) is near that of atmospheric pressure. Thus, the deformation is accomplished by application of pressure vector to the solids in the sample in a cylinder with infinitely resistant walls, where water escapes the system as deformation occurs. This configuration results in two types of movement—vertical and lateral—as the materials descend in the tube and flatten toward the walls. The deformation is not of only one kind: one is compressive and due to collapse, and the other, due to lateral movement, has a certain shearing component. A second aspect, and one of great importance, is that the sample is generally observed for a short period of time (hours). This amount of time is usually sufficient to permit the compressed water to escape the system, allowing a minimum of hydrostatic internal pressure—but not long enough to permit the attainment of structural equilibrium. Consequently, one has information and a series of numerical formulations designed to explain these results on a limited time scale, but not necessarily on a scale pertinent to the problem of natural compaction. Therefore, one must take the interpretations of laboratory data as a first approximation to the problems of the compaction of earthen materials.

This method of compaction is most closely related to modern rammed methods, in which high compaction pressure is obtained and maintained for several minutes.

Dynamic Compaction: Rammed Earth and the Proctor Test (Craig 1992, 24–29)

In the 1920s, a standard test was developed to determine the amount of compaction that a soil or earthen material will undergo under dynamic compaction. This is the Proctor test. It involves the dynamic compaction of a sample by allowing a weight (2 lb.) to fall a given distance (1 ft.) a given number of times (25) on a sample of a given thickness in a tube of a given diameter. The density of the material is then measured, and it is related to its resistance to mechanical deformation. This test is done several times on the soil or earthen material at different water contents. The maximum water content is that of the field drained saturation of the natural material, which depends on its porosity and the absorption of water by the clay-sized particles. Typically, the density initially decreases as water content increases, then it increases for a given material until it passes through a maximum. This maximum is 6%–8% less than the maximum (saturation) water content of the sample. Different sample conditions will give a line of optimum density for the test. The laboratory tests consist, then, of hydrating a given material at different states and performing the compaction experiment in order to determine the water content that gives the greatest density. In the field, one attempts to control the water content when compacting the soil-earthen materials. This procedure is critical for road building and the construction of other earthen works. The compaction in the field is usually performed by heavy vehicles moving over the earthen materials. This compaction process is dynamic—hence the application of the Proctor test, where the application of pressure is of short duration by gravity fall of a heavy object.

In this Proctor test, the critical point is that the optimum situation is one where a three-phase system (solids, water, and air) is present in the sample. The air space is necessary to allow the compaction of the sample without its attaining the state of liquid-solid. In this state, the water would resist the applied pressure by hydraulic conductivity, and the sample would not be further compacted. The ideal state of the Proctor test is one in which the water can be displaced locally, and the problems of displacement of water due to low permeability are overcome. Hence the high water content samples show a sharp drop in final density. In optimum conditions, air-water-solid, the excess water expelled by initial compaction fills the air space, which allows the solids to come in contact in the presence of water. When the water content is too low, there is poor compaction (low density), due to hardened, rigid masses of clay. Thus, some water is critical to good compaction of earthen materials under dynamic conditions, but enough is enough. As it turns out, this high-density state attained by dynamic compaction is very robust and resists very well mechanically. Such is the method used for many centuries by builders of rammed earth structures (without the help of Mr. Proctor).

If one compares the density attained with the dynamic compaction of soils and the compaction one would have under the same pressure conditions in a static test for long periods of time (days), the dynamic compaction is less efficient than the saturated conditions under oedometric conditions (results of personal experiments). Dynamic compaction gives lower mechanical resistance than static compaction (unpublished data of the author). However, the dynamic compaction is rapid and still highly efficient. The optimum grain size distribution in earthen materials for such compaction has been determined over many years' experience (Houben and Guillaud 1994).

What interests us here are the reasons for this efficient dynamic compaction and its long-lived effect. As we have seen, the grain shape of natural materials changes with their size. The clay-sized particles are essentially those of the clay mineral family, and they are tabular or sheet shaped. Silt and sand grains tend to be rounded because of the crystallography of these materials (quartz and tectosilicates). The large grains come into contact in few points because of their shape. The clays can fill the interstices, but also—and probably more importantly—they can form films at the contacts of the grains. The clay-sand contact is probably the key to the stability of earthen structures. Unfortunately, the exact nature of the contact and its stability are not known at present.

Grain Shape and Compaction

The difference in shape between clay minerals and tectosilicates (quartz, feldspar) is of great importance with regard to the effect of compaction. Sand, mostly quartz, grains are usually rather round in shape. They can be considered as approaching a spherical shape. Clays, on the other hand, are sheet shaped or tabular or they have a long rectangle shape. When sand is compacted, the average porosity (i.e., volume not occupied by the sand grains) is about 30%. When clays are compacted in the most dense manner, the porosity is near 5%–10%. Thus, the potential for compaction of clays in their initial, natural state is much greater than that of sand.

Grain Shape Effects on Compaction Curves

First and foremost of importance is the fact that the soil and earth materials subjected to pressure constraints are generally heterogeneous in grain size and grain shape. This means that, in each sample, dynamic solicitation and the adjustment of the individual grains to it will depend largely on the neighbors present and the organization of those neighbors. The proportions of the differently sized and shaped grain components are important, in that they will determine the bulk response of the materials. For example, small flat grains (the clays) will not respond to pressure vectors as do rounded, coarser sand grains. Clays tend to slide on one another, while sand grains tend to push into one another in a rigid manner, and they eventually break at points of contact where stress is concentrated. Clays, in general, will behave in a plastic manner, while sands will behave in a fragile manner. Thus, the size distribution of the components is important because the materials are not homogeneous in their shapes as a function of size, and responses to pressure will depend on this size-shape function.

The compaction of sands is small, while that of clays is great. The effect of mixing different types of particles is not linear. This observation suggests that there is a significant amount of interstitial filling of small clay particles between sand grains in the higher proportions of sands—and hence, little initial compaction for the coarse grain size. Well-sorted sand grain assemblages (homogeneous in grain size) will have up to 40% porosity. This porosity will be filled in the low-clay-content mixtures by the clay particles. Hence, the amount of compaction will not be important, as the clays fill in the holes. As clay content increases beyond 60% of the mixture, the compaction increases greatly. At this point, the spaces between the round sand grains are filled, and the plastic effect of the clays becomes very apparent.

Therefore, the relative proportions of the different grain sizes are an important consideration in dealing with soil and earth materials, because the shapes and response of the grains of different sizes are different. The more large grains present, the more rigid will be the behavior of a sample, and there will be a stronger tendency to deform the material by grain breakage. Here the resistance to compaction is great at lower pressures. The more clay present, the greater will be the tendency to deform the material in a plastic manner—i.e., by flow of the solids as the clay grains slip over one another in order to accommodate compressive forces.

Associated Fields of Research Applicable to Earthen Compaction

Agriculture (Horn et al. 2000)

There is a great deal of information available on the dynamic compaction of soils in the agricultural literature. The problem of densification of soils under the impact of heavy farm machinery is very critical. If a soil is compacted under "Proctor" conditions—i.e., optimum relations of solids, air, and water—the resultant densified soil mass is unusable for several years in the agricultural context. Hard, compact soil masses are not good for the root growth of new crops. Therefore, there is a great amount of literature devoted to the conditions under which different soils can be compacted.

The farm problem is the inverse of that concerning earthen construction. The farmer wishes to get into the field, on his very heavy equipment, as soon as possible in the growing season, before the drying effect hardens the soil. However, if he is in the field too soon, the compaction effect will do great harm to the soil material in his field. The studies of compaction in farming are interesting to us, in that they are due to a dynamic pressure impact, and they deal with the transmission of the compaction effort into the earthen material. The deeper in the soil one goes, the more dispersed the dynamic energy of the compaction will be. Other aspects of the extent of the compaction process are the organic matter content of the soil, the soil texture (grain size distribution), and, of course, the water content. All of these terms come into play in problems of earthen construction. Thus, it is often useful to consult this agricultural literature in the context of compaction, along with the information found in the literature concerning engineering problems.

Another aspect of soil compaction research that is interesting to investigators dealing with earthen building materials is the importance of compaction on water flow or permeability. In agriculture, permeability is extremely important. Plant roots need air to survive. Hence the studies of compaction and its effect on soil moisture content and water flow are well detailed.

Foundry Molds

There are other areas that can supply practical information concerning the effects of sand and clay compaction. For example, in the metal industry, molds into which molten metal is poured are made of sand-clay mixtures. The components are clean quartz sand and the clay mineral smectite. The ideal mixture is 6%–8% clay and the rest sand. This material, when compacted in a slightly wet state, is very stable under the solicitation of molten metal pouring. It is known that the clays form thin coatings on the sand grains, and in doing so, they come into contact between sand grains. Since the porosity of well-sorted sand is near 30%, it is obvious that the clay does not fill all of the pores. Therefore, the presence of clay will be efficient only as a relay between the sand grains as they are compacted to form the molds. Clay content will be small, and porosity will be great. However, even if the density is low, the material will be highly stable.

Stability under Load (Marshall, Holmes, and Rose 1996, 29–49, 229–45)

A field of research that seems to be rarely explored with regard to ancient earthen structures is their physical stability as a function of time. Deformation with time is generally called plastic behavior. Once a structure is obtained, either by the adobe or rammed earth method, the forces of the structure (load pressure) exert a force on the materials that is resisted by the inherent strength of the material. Stone and fired brick have a strong resistance to plastic flow, and major failures are due to internal cohesion or crushing strength. However, clay materials (where the clays are still intact and can attract water layers to their surfaces) are subject to plastic flow or deformation that is not limited in time.

Kinetics of Plastic Deformation (Creep)

It is well known, but rarely admitted, that earthen materials tend to deform plastically, with time and over long periods. This is known as creep, and the general term, in engineering studies, is *settling*. Conceptually, the compaction of earthen materials occurs in two steps, one of primary and another of secondary compaction. The time lag between the two processes is assumed to be that necessary for the water of the sample to escape. Samples with a low permeability will compact more slowly than those with a high permeability. Hence, the curves of compaction as a function of pressure are not constant but are, instead, a function of time, even though they are represented as absolute values in engineering reports and studies in soil deformation. As the time of compaction is increased, the curves tend to shift to higher compaction for the same pressures. These curves should converge at very high pressures, as matter is not infinitely condensable. In theory, the ultimate compaction would be near the absolute density of a given material. For clays and quartz, this is near 2.5.

Observations by Feda (1992) indicate that such stepwise compaction of clay-rich materials can continue for up to three years in laboratory experiments. Crawford and Morisson (1996) have observed settling (creep, or plastic flow) in basement materials of the Frazer River delta in Canada that has continued for thirty years. Thus, the manner of deformation of clay-rich materials can be one of very slow, but continuous, plastic behavior. The higher the proportion of clays in a soil or earth, the stronger the tendency to flow or have a plastic behavior and to show features of settling.

Wetting and Drying

Another aspect, and probably of highest importance, is the effect of changing the humidity of an earthen structure. If the values of water content for Proctor (dynamic) formation are precise, what happens as the material dries or is subsequently wetted? One has to consider not only the ideal or initial conditions of building but also the possible variations with time in the life of an edifice.

Yet another aspect of humidity change is one of cycles. Wetting and drying are important in the formation of cracks in soils and clay-rich materials (Pillai and McGarry 1999). Recent studies (unpublished work by the author) of soils shows that wet-dry cycles tend to associate the clay particles into aggregates, forming cracks at their borders. In this evolution, the position of the pore spaces is changed from dispersion in the material (a rather stable condition) to high concentration, where cracks will destabilize the earthen material structurally.

Conclusions

This discussion has offered only a brief outline of the problems and the knowledge of the compaction and drying processes used to produce the elements of earthen structures. In one process—adobe—drying is the means of forming stable, dense, coherent materials that resist crushing. The internal coherence is due to the approach of clay surfaces during the drying process. The second method—rammed earth—uses a mechanical force that compacts the clay particles to form internal cohesion. In this process, plastic deformation during the compression stage is assured by the presence of a slight water content, so that no dried particles form, and clays slide over one another to form the most compact state.

Certainly the two different methods of forming earthen materials into building elements require differences in the initial constituents. The limits and optima of natural earthen materials, especially in relation to their grain size distribution, are not known with precision. From the perspective of conservation, it is necessary to understand how a system works in order to correct it or intervene in it. The fundamental question that persists is: why do clays stick together? Sand grains tend to fall apart on drying, but clays become harder and harder in a dry condition. What makes clays so hard? Some theories indicate that it is by electrostatic attraction. However, some clays remain stuck together and others are easily unbound when rehumidified. An answer to this fundamental question of why clays stick together will lead to an essential understanding of earthen building materials, their formation, and their performance.

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Characterization of Earthen Materials

By Hubert Guillaud

Earthen materials, like any other building material, can be tested so that their behavior and performance can be characterized and better understood. Characterization procedures for most industrialized construction materials (e.g., stone, brick, wood, concrete, steel, etc.) are well established and standardized; this is not yet the case for earthen building materials, despite notable progress in the last decade.

Developments in sustainable, or "green," architecture, technologically appropriate construction, and low-cost housing, among others, have aided progress in the realm of new earthen construction. In contemporary building, characterization techniques assist in the attainment of a certain level of building performance or behavior through the selection and composition of materials. However, characterization procedures in the field of contemporary earth construction are not, in many cases, directly applicable to the conservation of earthen archaeological sites and historic structures. In conservation, the purposes and methods of characterization are more diverse, because conservation involves both existing and newly composed materials. Characterization aids in the development of new earthen materials used for conservation efforts (e.g., renders, repair mortars, replacement adobes, capping, etc.), so as to both optimize performance and achieve compatibility with existing materials. Characterization of existing materials can also offer insight into how and why they have changed over time, how they behave and will behave in the future, and how best to treat them. Although many characterization procedures for new earthen construction have informed preservation and repair efforts to date, methods have not been sufficiently adapted for the purposes of conservation.

Properties of Earthen Materials

Characterization involves testing the properties of materials that influence their behavior and performance in construction applications. In new earthen construction, the literature identifies the following properties and characteristics as significant to performance:

- particle size distribution
- plasticity (workability and water content)
- cohesion
- compactability
- shrinkage
- porosity, permeability, and capillarity (void indices)
- erosion resistance
- chemistry
- mineralogy
- classification

However, little research has been undertaken to determine the correlation of the above properties to performance in conservation applications; nor has there been significant investigation of additional properties that influence behavior as part of conservation interventions. In discussing the compatibility of restoration techniques with old materials, Peroni and colleagues (Peroni et al. 1982) note the importance of compressive strength, thermal expansion coefficients, porosity values (void size and distribution), soluble salts content, permeability to water vapor, and extraction of alkaline material. R. Hartzler (1996) gives a description of the main properties of earthen mortars and suggests procedures for characterizing them that are derived from ASTM standards for cement mortars. The limited literature suggests that, in addition to the aforementioned properties related to new earthen materials, the following may be relevant to conservation applications:

- compressive strength
- bending strength
- shear strength
- hardness
- adherence (especially for renders)

- expansion and contraction coefficients (freezing and thawing, thermal)

While these indications of properties provide helpful guidance, the body of literature—or the lack thereof—suggests that no systematic research has been undertaken to identify those properties most germane to the development of earth-based conservation materials and interventions, or to elucidate how they are relevant from a performance-based perspective. Thus, conservation of earthen architecture often involves cobbling together insufficient information from new construction research and empirical testing in the field, in order to plan and design interventions.

Field and Laboratory Analyses

The characterization tests for earthen building materials most commonly referred to in the technical and scientific literature are mainly derived from geochemistry; earthworks engineering (e.g., road building); and research related to "porous" materials, mortars, and concrete. Testing generally falls into two categories:

- *Field analyses:* These are tests carried out in the field, mainly in the form of macroscopic observations and simple, quick manual tests that use easily accessible and inexpensive equipment. They allow one to assess and to predetermine certain properties and characteristics of the material.
- *Laboratory analyses:* These are tests carried out in a laboratory with microscopy and other means, often complementing field analyses when confirmation or additional information is needed.

The literature covering the field of earthen construction fairly systematically refers to the use of field analyses for characterization when new building materials are prepared. By contrast, the literature addressing architectural conservation refers primarily to the use of laboratory analyses. This dichotomy may reflect the different attitudes of the community of professionals dealing with new earthen building versus those dealing with conservation of earthen heritage, or it may be indicative of the resources available to each. Regardless of the cause, there is a fundamental need to foster dialogue between these communities, as well as to improve the practical correlation between field and laboratory analyses.

The following discussion explores the existing field and laboratory analyses associated with the aforementioned properties, in an effort to outline the procedures currently being applied in research and practice and to explore their bearing on the understanding and preparation of earthen materials.

Particle Size Distribution

Particle size distribution, also referred to as texture, is defined by the various fractions of particles (in nature and quantity) making up the soil. Particle sizes, going from the finest to the coarsest, are as follow: clays, silts, fine sands, coarse sands, gravel, and stones. Most authors note the importance of particle size distribution in material performance and refer to several procedures for characterizing this property.

H. Houben and H. Guillaud (1984) discuss the following preliminary field analyses to identify particle size:

- visual examination of the rough texture of a soil in a dry state, taking the fine fraction after removing its coarser elements (stones, gravel, and coarse sand);
- testing by grinding the soil between the teeth, which allows one to assess the main particle size component in sands, silts, or clays;
- the touch test—rubbing the soil between the fingers and the palm of the hand, which also allows one to assess the main particle size component;
- the wash test, which, depending on how hard it is to rinse the soil off one's hands, suggests the main particle size component;
- the simplified sedimentation test, in which a mix of soil and water is shaken and decanted in a flat-based cylindrical jar, giving an indication of the quantity of the various particle size proportions deposited.

In the laboratory, quantitative particle size analysis by sieving, which includes measuring the rate of sedimentation to identify fine fractions of $Ø < 0.08$ mm, is most commonly mentioned in the literature and is fairly systematically used in practice. There are very comprehensive descriptions of the procedure in H. Houben and H. Guillaud (1984) and in J. M. Teutonico (1988). L. Dassler (1990) notes the advantage of carrying out "qualitative" sedimentation analysis using the procedure established by J. Ashurst and N. Ashurst (1988). R. Hartzler (1996) refers to particle size distribution analysis by sieving, in accordance with ASTM standard D422 (American Society for Testing and Materials 2002) and recommends the addition of a dispersing agent, sodium metaphosphate, to the clay fraction, for the particle size analysis carried out in a solution of deionized water. He also suggests that this particle size analysis should be complemented by a description of the soil particles, notably of the > 0.075 mm fraction, by examining it under a stereoscopic microscope under a source of halogen lighting produced by fiber optics. This analysis enables one to determine the roundness and the spheroidicity of the particles, their color, and the presence of organic matter.

Although basic particle size analysis by sieving is relatively simple to carry out and requires minimal laboratory equipment, analyzing the proportion of fines by sedimentation is a long process, since it can take nearly forty-eight hours. Several researchers have therefore attempted to develop simplified procedures, essentially to gain time, while also aiming to reduce the laboratory equipment needed and above all to reduce the costs of the analysis. A. Mesbah and M. Olivier (1990) suggest a simplified "rapid" particle size/sedimentation analysis. This analysis uses the Archimedes principle of displacement to determine the dry mass of the various particle size proportions of the material. The material is introduced into a graduated test tube immersed in a flotation basin. By simply noting the levels of water inside and outside the test tube, the level of displaced water, which corresponds to the volume of the material, can be calculated. The weight of the material is obtained by multiplying the volume by the dry density of the particles of the material. This procedure avoids the use of scales and of an oven to dry the wet material and considerably reduces the time required for classic quantitative particle size distribution.

Recent developments in analytical techniques now allow one to characterize texture and determine particle size distributions using laser techniques. The literature makes only a few references to this, notably in a report by H. Houben (1997) on the Desert Development and Training Building of Sadat City, Egypt. The procedure utilizes a light-scattering (LS) laser particle size instrument that allows for very rapid (65 sec.) analysis of quantitative grain size distribution, giving very precise information on the volume of the particles across a gradation from 0.04 µm to 2000 µm. This laser analysis allows accurate measurement of the diameters of sensitive particles, corresponding notably to active fines, and also of sandy structuring fractions. Though effective, the procedure requires a well-equipped laboratory and is not commonly used.

With regard to particle size analysis, the literature makes a number of references to the issue of interpretation. A. Demehati (1990), of the Moroccan Laboratoire Public d'Essais et d'Etudes (LPEE) of the Centre de Réalisation de la Recherche (CRR), suggests a simplified interpretation of the particle size distribution curve by knowing the percentage values by weight of certain fractions of particles. In the author's view, the percentage of elements of Ø > 2 mm and that of elements of Ø < 80 µm allow the overall texture of the soil to be assessed. In addition, P. Poupet and C. A. de Chazelles (1989), referring to analyses carried out on the archaeological site of Lattes, France, suggest that interpretation of classic, cumulative particle size distribution curves should be complemented by interpretation of cumulative semilogarithmic curves using the Rivière method, which requires the use of equivalent diameters of particles and of reduced percentages. Equivalent diameters correspond to the transformation of real diameters obtained by sieving. Reduced diameters take into account the limits of the particle size distribution spectrum in addition to the fine fraction actually measured. In application of the classic method, the parameters or indicators of particle size distribution changes serve as a basis for interpretation, but they also characterize the particle size distribution curve as a whole rather than for particular points, such as particles (or numeric particle size distribution indicators). An XM average characterizes the average coarseness of the sediments. The medium logarithmic differential, MLGD, allows one to specify the degree of change in the sediments depending on where they are deposited upstream and downstream in watercourses. The absolute logarithmic differential, ALGD, compared to the MLGD, depending on the size of the differential recorded, enables the multimodal nature of the distribution of sediments to be specified. Two purely numeric parameters, 11 and 12, characterize the distribution independently of its actual range. A particle size distribution indicator of N also allows the degree of change of sediments from upstream to downstream in watercourses to be characterized, and this complements the MLGD reading. Thus, taken as a whole, these particle size distribution indicators enable the origin of the materials, how they were carried and deposited, how they have changed or been transformed—in short, their history—to be specified.

Plasticity

Plasticity relates to the behavioral properties of soil in the presence of water. This property is difficult to assess through field analyses, though the following tests are utilized:

- *the consistency, or string, test,* which consists of rolling a ball of fine soil into a thin "string," which should start to

break up at Ø = 3 mm. A procedure of reshaping the material into a ball and crushing between the finger and thumb allows one to estimate the clay or the sand-silt fraction;
- *the cohesion, or cigar, test,* which consists of making a cigar-shaped roll of soil (Ø = 12 mm) and estimating its clay content by the length at which the cigar breaks when it is rested on the palm of the hand and gentle pressure is applied. This test is akin to the ribbon test, in which the cigar is flattened between the thumb and forefinger, and the length of the "ribbon" is similarly measured at breaking point.

In the laboratory, the primary tests for characterizing plasticity are methylene blue analysis and, more popularly, the Atterberg limits, which include the liquid limit, or LL; the plastic limit, or PL; the shrinkage limit, or SL; and the plasticity index, or PI. The Atterberg limits, devised by a Swedish scientist of the same name, are commonly cited in the literature. H. Houben and H. Guillaud (1984) and J. M. Teutonico (1988) provide a detailed description of the testing procedures. Many authors, including L. Dassler (1990), A. Demehati (1990), P. S. Jerome (1991), and R. Hartzler (1996), note plasticity analysis using the Atterberg limits as vital to earthen material characterization, and they often reference applicable ASTM standards. Of particular relevance is the relationship among the indicative limits of the Atterberg procedure. The correlation of the liquid limit (LL) and plastic limit (PL) values enables one to specify the value of the plasticity index (PI) and hence predict the potential deformation of the material (the higher the PL, the more the soil will swell when wet and shrink when dry). Comparison of the PL to the LL can provide the following information about plasticity and associated properties of earthen materials:

- identification of the kind of soil present, by reference to the common geochemical classifications—the French Ponts et Chaussées (P and CH) classification and the United States unified soil classification system (USCS).
- specification of the degree of cohesion of the soil by characterizing it in one of the following four categories: very highly cohesive, highly cohesive, moderately cohesive, and slightly cohesive.

Likewise, correlation of the PL and the quantity of clay fines (by percentage) provides additional insight into material behavior, including:

- an indication of the degree of activity of the clays of Ø < 2 μm, with the results categorized as very active, active, moderately active, or inactive;
- as discussed by H. Houben and H. Guillaud (1984) and A. Demehati (1990)—regarding the relationship between PL and the percentage of fines of Ø < 2 μm—identification of a value of activity coefficient (AC), enabling one then to refer to the values established by Skempton to determine the activity of a soil (for a slightly active soil, a value of AC ≤ 0.75; for a normally active soil, a value of between AC ≤ 0.75 and AC ≤ 1.25; for an active soil, a value of AC ≥ 1.25; and for a very active soil, a value of AC > 2);
- an indication of the expansion properties of the fine fraction (Ø < 0.4 mm), categorized as very high, high, moderate, or low.

Other authors, though few, equally note the advantage of specifying the methylene blue stain value. They refer principally to the French NFP 18 592 standard (Association Française de Normalisation 1990). This is referred to in A. Mesbah and M. Olivier (1990), in A. Demehati (1990), and in H. Houben (1997). The methylene blue value is an identification parameter, providing an overall measurement of the quantity and the activity of the soil fraction contained in a sand by comparing the blue value to the total specific area of the clays. It measures the capacity of the fines in suspension in water to adsorb methylene blue in successive doses, with samples placed on a filter paper until a persistent stain with a halo of blue is obtained. In addition to enabling one to assess the activity of the clays, the blue value also allows one to identify certain harmful characteristics, such as water absorption, cohesion, and swelling.

Cohesion

Cohesion refers to the capacity of particles to bind together and the bending strength of the coarse fraction (Ø < 2 mm). In the field, cohesion can be relatively well estimated using the following tests:

- the dry compressive strength test, in which pressure is applied to a ball of dry soil, which is then broken and crumbled by hand to assess, depending on how easily it breaks, the proportion and the purity of the clays, or to assess if they are silty or sandy in nature;
- the cohesion, or cigar, test (as discussed above).

In the laboratory, the main tests used for evaluating cohesion properties are the wet bending test or the "8" test perfected by the German scientist Niemeyer in 1944 and included in the German DIN standards in 1956. Although it is cited in the literature by H. Houben and H. Guillaud (1984; 1989; 1994, 62), this test is seldom used in practice.

Compactibility

Compactibility refers to the point at which the material reaches its maximum dry density, or so-called "optimum" water content, or OWC, under conditions of compaction. This property also provides information about the porosity and the permeability of the soil. The field tests allowing one to gauge compactibility are highly empirical and consist mainly of compacting the ground or of compacting the soil in molds to make blocks. The use of a pocket penetrometer then provides a rough indication of this property by giving an approximate value of the density of the soil. In the laboratory, the property of compactibility is measured mainly by the standard or modified Proctor test, a geochemical test referenced by the American Association of State Highway Officials. Though the testing procedures exists, the literature suggests that analysis of this property has minimal importance for the understanding or prediction of the behavior of earthen materials (Houben and Guillaud 1994, 60–61).

Shrinkage

Shrinkage refers to the property of the soil to change in volume in the presence of water. In the field, shrinkage is evaluated by using molds to form disks of fine soil (Ø < 0.4 mm), then measuring the reduction in the diameter of the disk compared to that of the mold. This procedure provides a preliminary indication of the quantity of clays present and of how active they are. In the laboratory, the linear shrinkage test designed by Alcock is employed, and it is commonly cited in the literature (Houben and Guillaud 1994, 49).

Though shrinkage is an important property that significantly influences the behavior of earthen building materials, few authors discuss the characterization of shrinkage in their analyses. R. Hartzler (1996) advocates linear and volumetric shrinkage testing, in accordance with ASTM standard D4943 (American Society for Testing and Materials 1995), with a view toward predetermining the presence of unstable clays (such as montmorillonites, smectites, and bentonites). In addition, A. Demehati (1990) suggests that a "relative shrinkage" (RS) value should be taken into account. The RS is obtained from the interaction of several parameters—i.e., the product of the difference between the liquid limit (LL) and the shrinkage limit (SL), multiplied by the product of the apparent bulk density (γd) divided by the density of water (γW). The result of this equation, in percentages, gives the measure of this relative shrinkage; thus, for RS ≥ 70%, soils that shrink a great deal; for 50% ≤ RS ≤ 70%, soils that shrink moderately; and for RS < 50%, soils that shrink very little.

Porosity, Permeability, and Capillarity

The properties of porosity and capillarity of the material are of particular significance with regard to conservation of earthen architecture, as they are often indicative of the material's susceptibility to degradation. Though most analyses of these properties are carried out in the laboratory, A. Hakimi and A. Acharhabi (1987) of the LPEE of Casablanca, Morocco, present a field test for permeability that assesses the possibility of rainwater infiltration through a wall. The test does not require a great deal of equipment, is easy to carry out in situ, and lasts only half an hour for each location on the walls tested. It consists of using a permeability box or "chamber," i.e., a rectangular box applied to the wall enabling a surface of water penetration measuring 16 x 34 cm to be isolated. The edge of the chamber is made watertight either by a rubber band or a strip of mastic. The chamber is held against the wall by a metal knee brace. Once in place, the chamber is filled with water through a hole in its upper side. When the chamber is full, the water level is kept constant through the use of a graduated Mariott tube, the flow from which compensates for the amount of water percolating through the wall. The amount absorbed by the wall under an average constant load of 15 cm can therefore be measured, taking the surface of water loss as a reference. The test can be of interest for the most exposed parts of earth walls, either the base of the walls, which can be exposed to splash back, or the facades most directly exposed to rain. It is probably of less interest in other situations (normal walls and less exposed facades).

With regard to laboratory analyses, P. S. Jerome (1991) refers to a method for calculating the ratio of voids to the solid part of the material, using quantitative stereometry. She also mentions the advantage of carrying out a microscopic examination in reflected light to ascertain the dimensions and the distribution of cracks, pores, and voids more accurately, and thus to specify, by calculating a void index, the porosity of the material. This examination is equally applied to the detection of the presence of salts, which can cause a process of crystallization and expansion in these cavities. S. Skibinski (1991), with regard to tests carried out on adobes of the Peruvian site of Cahuachi, notes the interaction between measures of specific gravity (g/m^3) and of gravimetric absorbability (%) to determine the open porosity of the volume (%) and the speed of capillary rise (cm/min.).

M. Dayre and E. Kenmogne (1993) consider the influence of soil structure on humidity transfer or, more precisely, on the influence of the particle size distribution of soils on water migration processes within compacted earth blocks. They suggest that this link should be studied by gamma ray spectrometric analysis.[1] The results obtained, shown in the form of hydric profiles (curves showing the change in water content over time) allow one to determine the values of hydric diffusivity through the material tested. Dayre and Kenmogne consider that "of the structural parameters likely to be paramount in transfers of moisture, porosity, the porosity value (void index) and the specific area play a major part." They suggest using gammametric analysis in connection with measures of porosity and permeability and hypothesize that the observation of high levels of diffusivity can be explained by the presence of a small proportion of small pores, which are the source of capillary rise. In the opposite case, low levels of diffusivity can be linked to a strong specific area slowing transfers and reducing permeability. S. Skibinski (1991) also mentions a study of the transfer of phreatic water by capillary forces at the base of adobe walls, based on VHS multispectral image analysis, using a computer. This method was devised by the Institute of Research and of Conservation of Monumental Assets of the Nicholas Copernicus University in Poland. The visual spectra of the wall are analyzed on red and blue monochromatic scales. Changes in the temperature of the surface of the wall are shown in variations of red. Differences in the physical properties of the material are described by variations in the color blue. These analyses prove the presence of capillary water in the base of adobe walls.

[1] This consists of analyzing the effects of gradual humidification resulting from capillary rise in a block, the base of which remains in water. By vertically displacing the source-detector unit, the gammametric plate enables one to monitor changes in the volume water content at different levels of the height of the sample. The dry block should be first scanned before wetting, and then successively scanned until the constant water content value is obtained. The volume water content θ relates the volume of water to the total volume of the sample containing it. The mass water content w is linked to the specific gravity of the material by the expression $\theta = w \times dd$, in which dd is the specific gravity of the dry sample.

Resistance to Erosion

Analyzing a material's resistance to weather-based erosion consists of exposing the material to artificial rain, simulated in the form of a constant pressure perpendicular to the surface, controlled by a manometer, for a specific time cycle. Per ASTM standards, the average depth of the largest holes observed on the material provides an indication of its erosive properties. This test is generally considered to be very tough, and most traditional and historic earthen materials—which have not been stabilized or consolidated—do not hold up to it. Practitioners have thus been obliged to modify or adapt the standardized procedure. In Australia, L. M. Schneider from the Chatswood National Building Technology Centre has adapted the ASTM standardized procedure by recommending spraying at a constant pressure of 50 kPa for one hour (Middleton and Schneider 1987). The maximum depth of erosion permissible is 10 mm. R. Andrews (1990) has focused on implementing a simplified, field erosion test with the Deakin University of the State of Victoria. This test consists of exposing an adobe block placed at an angle (of 30°–45°) to a constant drip for half an hour, 1 L of water dripping from a height of 40 cm above the block. Resistance to erosion is considered to be good between 3 and 5 mm and satisfactory between 5 and 8 mm.

Chemistry

The chemical activity of a soil can be roughly assessed in the field using a smell test, which essentially indicates a presence of organic matter, or, more effectively, it can be assessed with a pH measurement. In addition to simplified measures using pH paper or other calibrated kits, S. Skibinski (1991) details a more elaborate laboratory procedure, applying Polish standards. This consists of using ground-up samples of material in order to obtain a grain size < 0.104 mm. This material is then dried at a temperature of 60°C, and the analysis is made on extracts to which distilled water is added in quantities of 10 cm^3/g. The samples are then mechanically shaken for one hour and filtered twice per decantation using a 100 cm^3 pipette. These watery extracts are then measured with a pH meter.

Additional laboratory tests using calibrated reactive products allows the chemical components of the soil, and particularly salts, to be identified, which are critical to an understanding of behavior and material performance. L. Dassler (1990) and R. Coffman and colleagues (Coffman et al. 1990) suggest that it is possible to determine the relative quantity of organic components in the soil using a combustion test. This test results in a loss of weight of the sample exposed to fire, resulting from evaporation of the incorporated water or the destruction of the incorporated organic matter, as well as from the volatile gases contained in the nonorganic matter (CO_2). Another means of detecting the presence of organic matter is detailed by H. Houben and H. Guillaud (1984; 1994), who use a standard test accepted by the ASTM and the British Standards Institution (BSI). This consists of shaking a mix of soil and of sodium hydroxide solution and comparing the color obtained with a standard solution of tannic acid. The same authors also refer to a test for detecting humus using a preparation of soda solution (NaOH) or of potassium (KOH), in quantities of 300 to 400 ml diluted at 3%, to which is added a small quantity of crumbled dry earth (50–100 g). The mix is shaken vigorously, left to stand for twenty-four hours, and then observed. The color of the solution floating on the surface indicates the presence of humus. Also to be noted, C. S. Silver (1990) refers to analyzing the organic environment by applying histochemical colorants, notably to determine the presence of carbon hydrates, collagen proteins, and lipids.

In addition to analyzing organic matter, a few authors refer to detecting the presence of fibers in the material, in adobe blocks, or in earth-based renders. These consist of microscopic analyses of material samples carried out in polarized light and complemented by macroscopic and microscopic analyses of sections of samples (Dassler 1990), or microscopic examination in reflected light enabling one to detect the presence of straw or of its negative imprint after decomposition (Jerome 1991). In addition, J. Šrámek and L. Losos (1990) refer to the complementary nature of differential thermal analysis (DTA) and of thermogravimetry (TG), which, in addition to the mineralogical aspect, can also reveal the presence of organic matter. By monitoring the behavior of samples as the temperature is progressively raised (from 100°C to 900°C in the case referred to), it is possible to detect “exothermic” peaks, indicating the presence of organic matter such as chopped straw, animal hair, and humic components.

The presence of carbonates and soluble salts is undoubtedly the chemical property most cited by the majority of authors. P. S. Jerome (1991) refers to measuring calcium carbonate ($CaCO_3$) by carrying out analytical coulometric tests, applying the principle that calcium carbonate absorbs hydrochloric acid. This principle is also referred to by R. Hartzler (1996) with regard to analyzing soils in the southwest region of the USA, which are often rich in calcite, caliche, or calcium carbonate, or in dolomite, $CaMg(CO_3)_2$. The procedure is similar and is carried out with a solution of HCl diluted at 15%, which digests the soluble and acid fraction of carbonates. Other authors refer to the risk in manipulating such products and suggest less concentrated solutions (5%).

Regarding the analysis of salts, the literature refers mainly to carrying out microchemical tests, as cited by L. Dassler (1990), P. S. Jerome (1991) or R. Hartzler (1996). The material is tested with calibrated chemical products corresponding to precise types of chemical components: soluble salts, acid salts, and alkaline salts. R. Hartzler (1996) details a qualitative analysis of soluble salts that consists of immersing a sample of known mass in deionised water for three hours. The preparation is then filtered before being subjected to microchemical tests aimed at detecting the presence of soluble salts, among which the most active are chloride anions, sulfates, phosphates, and nitrates. H. Houben and H. Guillaud (1984; 1994) suggest a test for detecting chlorides and sulfates, by observing precipitations based on solutions of barium chloride (BaCl) for sulfates, or based on silver nitrate (NO_3) for chlorides.

P. S. Jerome (1991) provides further information on the types of reactive products that should be used in order to obtain the specific reactions of colored precipitation: for chlorides, a reactive agent made up of 3 M of nitric acid and 0.5 M of silver nitrate; for sulfates, 3 M of hydrochloric acid to which is added 0.3 M of barium nitrate solution; for nitrates, a solution of dyphenylamin in sulfuric acid; and for phosphates, 6 M of nitric acid with ammonium molybdate. The author highlights the importance of detecting nitrates—salts that are highly water absorbent and very apparent in evaporation-crystallization cycles and therefore particularly active in the degradation of the material. This process results from the migration of salts by capillarity, followed by crystallization in the voids (pores and channels) of the material, and by swelling as a result of evaporation. Such evaporation triggers tensile stresses, deteriorating the material. While noting that quantitative analysis of salts is more difficult to carry out on small, often not homogenous quantities of material, which may not be very representative of the more “global” nature of the material, P. S. Jerome (1991) notes that quantitative analysis of nitrates can be undertaken using EM Quant Test Strips and that of phosphates using a Hach Test Kit Model PO-24. Quantitative results are then provided in parts per million.

H. Houben (1997) also refers to analyzing soluble salts using X fluorescence. This procedure establishes the volume by percentage of a large typology of oxides, including magnesium oxide (MgO), calcium oxide (including free CaO), or the presence of carbonates, potassium oxide (K_2O), sodium oxide (Na_2O), and also of sulfuric anhydride (SO_3) or sulfates. Finally, in addition, R. Coffman and colleagues (Coffman et al. 1990) report on a program of research into the consolidation and preservation of historic earth structures conducted at the Getty Conservation Institute. They describe experiments carried out on samples of adobe blocks taken from various historic sites (China, Egypt, El Salvador, Israel), which are compared to adobes recently produced in New Mexico and California. The object was to detect the presence of soluble components (calcium and magnesium carbonates, sulfates) using ethylene diamine tetra acetic acid (EDTA) analysis, enabling the calcite to be dissolved without affecting the other components (complexification of the calcium ions). The EDTA analysis is complemented by leaching experiments. It is presumed that the leached material includes all the carbonates and salts (sulfates and/or chlorides) but not the silicates or oxides.

Mineralogy

Mineralogical properties are difficult to assess in the field and require specialized training, but observations of the geological or pedological character of an environment can provide important information for further mineralogical studies. These observations provide vital details about the profiles of soils and about the nature and composition of their main strata. Color examination, through the use of a Munsell chart, also allows one to assess a soil's main mineralogical features. Several authors (Dassler 1990; Silver 1990; Hartzler 1996; Jerome 1991) attach great importance to color examination and refer to the "visual-manual procedure for describing and identifying soils" in accordance with the Munsell chart and in application of ASTM standard D1535-80 (American Society for Testing and Materials 1980). P. S. Jerome (1991) nevertheless suggests that color examination in natural light should be complemented by an examination in reflected light with a stereoscopic microscope, coupled to a dionic, fiber optic light source. This additional examination allows the variations in color to be more precisely defined, thus refining the mineralogical identification and providing data on the porosity of the material.

Though the aforementioned procedures can provide a fair amount of mineralogical information, laboratory analyses provide the most accurate assessment of mineralogical properties. The literature most often refers to the mineralogical analysis of silts and clay fines using X-ray diffraction analysis (XRD) or DTA. With regard to mineralogical analysis by XRD, P. S. Jerome (1991) recommends supplementing it by a study of the diffractograms (which can provide interesting data on other traces of less immediately identifiable minerals) by observing samples of 30 µm using a petrological microscope, and by carrying out an analysis of the morphology of the clays using a scanning electronic microscope (SEM), which complements the energy dispersive X-ray analysis (EDXA) in a way that not only allows less apparent particles to be identified but also allows the composition of elements for more specific parts of the material to be specified. C. S. Silver (1990) also refers to the complementary aspects of XRD, SEM, and energy dispersive X-ray spectroscopy (EDS) analyses. In analyzing the properties of earth renders, mortars, and paints, R. Hartzler (1997), K. Fiero (1997), F. Matero (1997), L. A. Dix (1997), and J. Trott (1997) likewise used XRD and SEM analyses, complemented by an EDXA on the Mug House in Mesa Verde, Colorado. This enabled them to confirm the composition of the pictorial pigments previously identified by tests based on reactive chemical products.

With regard to the procedure for XRD analysis, L. Dassler (1990) further specifies that the samples prepared should be analyzed in a dry state and in a saturated (with ethylene glycol) state. The analysis in a saturated state makes traces of expansive clay minerals, such as smectites, appear more clearly. S. Skibinski (1991) suggests a sequence of analyses on a preparation of pulverized material, starting with observation using an optic microscope in normal and polarized light, then using an infrared spectrophotometer, and finally an XRD apparatus. Two types of samples are tested in Skibinski's procedure, which is based on a Polish protocol: samples subjected to spectrophotometric observation and using diffractograms of so-called oriented preparations (i.e., saturated in solutions of magnesium, potassium, and calcium salts, and of glycerin), and samples previously subjected to a thermal treatment at 550°C, to be analyzed using XRD.

J. Šrámek and L. Losos (1990) note the complementary nature of DTA and of TG, which provides a measure of the quantity and types of clay minerals. The spectrum of the various peaks obtained at different temperatures allows the clay minerals to be characterized.

With reference to the characterization of old mortars, work by G. Capannesi and colleagues (Capannesi et al. 1990) on instrumental neutron activation analysis (INAA) can be applied. This analysis allows concentrations of elements to be specified. Subsequently, treating the samples with HCl separates the soluble calcareous fraction and the insoluble sandy and pozzolanic fraction. The insoluble fraction is then subjected to another phase of neutronic activation to specify the elements of which the render is composed.

Classification

Pedological classifications can provide a great deal of insight into mineralogical properties. They generally take into account soil profiles as a whole and provide information on the ways in which they are formed and change. These classifications rely essentially on three sets of data:

- the degree of change and of differentiation of the soil profiles
- the way in which clays are formed and altered
- the basic physicochemical processes from which soil originates, often linked to organic matter

The simplified presentation of the classification of P. Duchaufour (Duchaufour, Faivre, and Gury 1976), suggested by Houben and Guillaud (1989, 46–47; 1994, 36–37), distinguishes between two main families of soil classification:

- Soils with a pedological genesis that is closely linked to changes in organic matter. They are generally found in temperate and cold climates.
- Soils with a pedological genesis that is fairly independent of changes in organic matter and is, rather, linked to the particular behavior of iron oxides and of aluminate. They are generally found in hot, more or less humid climates.

Specialized tables show how the various pedological classifications available correspond to one another, and pedological atlases provide very comprehensive descriptions of soils by related parameters, such as locality, topography, the nature of the parent rock (geology), climate, and vegetation. They give precise descriptions of the profile and the morphology of soils according to their various horizons: the surface A horizon, the structural or alteration B horizon, and the parent material C horizon. These atlases may also describe the main geochemical and biochemical characteristics by providing data on particle size distribution and the predominant clay minerals, on the absorbent complex, and on biochemistry. Finally, they can also detail the process of evolution of soils.

Geochemical classifications are also very useful in describing the main properties of soils in relation to their geochemical designation. Houben and Guillaud (1989, 76–77; 1994, 34–35) suggest a simplified version of the French P and CH and the United States USCS classifications. Soils are designated as coarse grained or fine grained, depending on the proportion of grain size fractions, the quantity of small particles, and their liquid limit.

Conclusion

Understanding the characteristics and the properties of earth as a building material requires us to go through a range of analyses and tests, in the field and in the laboratory. No fixed set of tests can be applied universally, as all conditions and contexts are different. Likewise, there is not enough research examining the properties of earthen materials and determining which are most important or relevant to performance in architectural applications. There is considerable agreement in the literature that particle size distribution, plasticity, and mineralogy are of particular import in characterizing earthen materials, but there is too little research to determine the relevance or priority of properties beyond these.

With regard to procedures, there is likewise a fair amount of agreement regarding laboratory analyses: sieving for particle size distribution, Atterberg analyses for plasticity, and XRD with supplemental testing to define the mineralogy of the clay fines. However, there is virtually no correlation between field and laboratory testing, so as to clearly identify which field tests can provide basic information in lieu of laboratory analyses or to determine how laboratory protocols might be adapted for field conditions. This is particularly important when the resources required for laboratory analyses are not available. Likewise, field analyses can potentially provide an important basis for determining which laboratory analyses are necessary or relevant to a particular situation—but greater correlation between lab and field are needed to achieve this.

Everything is a question of compromise—the most efficient compromise possible among the available equipment, skills, and financial resources and within the constraints or potentialities of certain contexts. Likewise, given the nature of earthen architectural heritage, significant consideration must be given to the extent to which any analysis destroys or alters original material. This particular constraint further underscores the need to be ever more informed about relevant properties and their associated analyses, and it demonstrates the reasons why further reflection and research are need to understand the links and adaptations between characterization procedures for new earth construction and for conservation.

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Recording and Documentation of Earthen Architecture

By Claudia N. Cancino

Heritage recording and documentation pertain to the methods by which significant data are collected, interpreted, presented, and archived in order to facilitate understanding of the configuration, evolution, condition, and context of heritage sites and objects. Physical recording and documentation involve scientific data collection over time, and they serve as a basis for decisions regarding diagnosis, treatment, and monitoring of a site. As an integral part of the conservation process, they cover all types of materials and sites, including those built of earth.

In the past three decades, the field of conservation has advanced methodologies for addressing deterioration mechanisms for site management and conservation. By documenting condition as the cumulative result of change over time or as the result of a direct impact, a conservator understands the process of deterioration, identifies a suitable intervention, and monitors the impact of the intervention.

The heritage recording and documentation literature covers a series of publications that vary in scope, from the documentation of movable objects to the remote sensing of cultural landscapes, cities, or archaeological complexes. With the ever-evolving technology in the heritage recording field, a series of international symposia and conferences has been held in order to collect and disseminate information relating to strategies and techniques for protection, preservation, and interpretation of earthen sites. There are no techniques exclusively applied to earthen sites, but many of the techniques developed in the field of recording and documentation in general can, and should, be applied to conservation processes related to earthen architecture.

Managing Change through the Use of Documentation

In the body of conservation literature, many authors emphasize the significance of recording and documentation as part of a comprehensive planning methodology for heritage management and as a tool for managing change (Pearson and Sullivan 1995; de la Torre 1997; Clark 2001; Demas 2002; Teutonico and Palumbo 2002). However, only a few texts deal specifically with the application of such methodologies to earthen architecture and archaeological sites.

The topic of site management has had fair discussion in the proceedings of the international earthen conservation conferences, held in Lima, Peru, in 1983 (ICCROM, Regional Project on Cultural Heritage and Development UNDP/UNESCO, and National Institute of Culture 1985); Rome in 1987 (Rockwell et al. 1988); Las Cruces, New Mexico, USA, in 1990 (Grimstad 1990); Silves, Portugal, in 1993 (Alçada 1993); and Torquay, England, in 2000 (English Heritage, ICOMOS-UK, and University of Plymouth Centre for Earthen Architecture 2000). A detailed survey and analysis (Matero and Cancino 2002) of published proceedings of these conferences reveals that site management planning exhibits a slowly rising popularity after 1987. This development reflects current changes in conservation thought and practice.

There have also been some case studies that have addressed issues of documentation for earthen sites as part of a planning methodology. In their work on the management plan for Chan Chan in Trujillo, Peru, Castellanos and Hoyle (2000) applied an approach similar to that of Pearson and Sullivan (1995), Sullivan (1997), and Demas (2002). The driving force in the plan's decision-making process was the site's cultural significance. The process of defining the significance of the site included the documentation of its physical and historical evolution. The plan incorporated the recording of the natural and social environments (legal, administrative, and social surveys), and this was the strongest component of the project.

Meinecke-Berg and Meinecke (1980) presented a strong case study of recording earthen sites in an urban context for basic and general planning purposes. Crosby

(1983) presented a maintenance guide for the historic church of Tumacacori in Arizona, USA. He first presented a brief program of work and then detailed the use of inspection forms as a means to document, but not evaluate, the site. In a project of similar scale, Van Balen (1990) proposed a methodology for the conservation and restoration of earthen structures. The proposal included the study of environmental factors and historical values and the evaluation of the architectural typology in a cyclical approach toward intervention. The proposal suggested that technical considerations in the conservation of earthen structures should be embedded in a global assessment to assure appropriateness of actions. Castellanos Ávila (1995) analyzed the problems regarding the management of earthen sites in the case of Paquimé, in northern Mexico, and concluded her research by describing problems associated with such archaeological resources.

Research at Mesa Verde National Park in Colorado, USA, represents one of the few cases in which the specific role of documentation and recording was developed and evaluated as part of a comprehensive conservation plan. Matero (2003) presented the final results of the nine-year phased conservation program. The program developed coordinated methods for the survey, analysis, stabilization, and interpretation of the masonry and prehistoric surface finishes in the alcove sites of Mesa Verde. Though primarily a case study, this article addressed in detail the theoretical and technical aspects of the condition survey as an important vehicle for material and site diagnostics (condition assessment), which must precede remedial and preventive interventions.

The problems facing heritage resources are rarely solved completely, but they can be managed. Such is also true for earthen sites and structures in general. The factors of deterioration will not necessarily disappear, but they can be controlled. Documentation and heritage recording, within the framework of integrated planning, are important tools in this regard. Though the cases mentioned above provide good insight into how techniques and tools are applied to earthen heritage, more research is needed to improve methodologies and to create comparative analyses of experiences.

Types and Levels of Recording and Documentation

Choices regarding type and level of recording and documentation depend primarily on the heritage resource (access, materials, condition) and the kind of information required. The following sections explore the literature related to five forms of documentation: inventories and large-scale documentation projects, historic structure reports, structural reports, condition assessments, and evaluation and monitoring assessments.

Inventories and Large-Scale Documentation Projects

At the beginning of the 1970s, after the development of several successful cultural heritage inventories, a series of international symposia brought together professionals in the field of preservation in order to discuss the significance of inventories and the classification systems for cultural heritage in various regions of the world.

The proceedings of the *Seminario Regional de Inventario y Catalogación* (Comisión Nacional de Investigación Científica y Tecnológica 1977) discussed the politics and methodologies of inventories in different countries in Latin America. The intention of these proceedings was to establish common and regional objectives and terms. In Europe in 1977, a meeting of experts on systems of inventorying cultural property was held in Warsaw (UNESCO 1977), which identified the need for guidelines to manage and create inventories with a common terminology throughout the world. A follow-up to the Warsaw meeting was held in Paris in September 1980.[1] The following month, the Colloquium on the Inventories of Cultural Possessions in Europe, held in Obernai-Bischoffsheim, France, brought together representatives of agencies responsible for inventories from a number of European countries. Its proceedings state that despite the use of defined vocabulary, inventories are meant to be used as a tool for planning and conservation. The conference declared that countries could not delineate preservation policies without acknowledging their resources (Ministère de la culture, Direction du patrimoine, Inventaire général des monuments et des richesses artistiques de la France 1984).

Soon after the 1980 Paris meeting, ICOMOS created an International Committee on Inventories and began to prepare a manual to analyze and compare the inventory systems selected in the 1980 conference, with the idea of presenting a methodological approach for the creation of heritage inventories. The *Manual on Systems of Inventorying Immovable Cultural Property* (Sykes 1984) was published as part of the UNESCO Museums and Monuments technical

[1] M. H. Sykes (1984) and C. Pernaut (1984) reference the September 1980 Paris meeting, though the author has been unable to locate proceedings or other documentation.

manuals and attempted to seek common terms, tools, and methods for identifying, analyzing, and managing cultural property. The publication described how to do inventories, but it did not address how the information was to be used.

Along with these international meetings, the development of digital technology advanced applications of systematic inventories in different countries. Jachimski, Weaver, and Letellier (1975) were the first to emphasize the fundamental need for easy storage, recovery, and comparison of recorded data. They developed techniques for different types of survey methods for the Canadian monument recording system. UNESCO applied and used inventories in order to define surviving historic fabric and to indicate measures for future preservation at the historic quarter of Al-Jamalyya in Cairo (Meinecke-Berg and Meinecke 1980).

A few years later, Ferrari (1984) stressed the risk of using advanced digital methods of inventory without considering that inventories are tools for historical and analytical research. Krzyanowski (1984) mentioned the importance of an interdisciplinary team for the creation of inventory systems. Nilsson (1984) explained the situation of inventories in Sweden and stated that inventories have to be integrated with the planning of a site. He stressed the advantages of incorporating other disciplines into the process as well.

By the late 1980s, inventories were in much wider use. Specific to earthen architecture, Bertagnin (1990) proposed an inventory method for different types of earthen buildings in the northeast of Italy, in order to classify different building pathologies. Degli Esposito (1993) developed a very simple survey method for earthen buildings in relation to social organization and patterns of evolution in the western district of Bologna. Selva (1993) used inventory methods to find relationships between typology and technology of earthen buildings located in the agricultural Participation of Cento within the Emilia-Romagna regional land. Orazi (1995) used a similar approach in his survey of adobe buildings of Sardinia. His studies contributed to the knowledge of different scales of intervention (“land body,” “building body,” and “constructional body”). Syrová, Syrový, and Kříž (2000) designed an inventory and documentation system for the earthen vernacular architecture of the Dyje Valley National Park in the Czech Republic. This survey was a pilot study and a methodological example of how a geographic information system (GIS) could be used to identify historical buildings that were neglected by the classic ethnographical literature.

Some inventories were particularly innovative in their methodology or approach and incorporated earthen architecture to varying degrees. In 1940–42, the Secretaría de Hacienda y Credito Público of Mexico undertook the *Catálogo de construcciones religiosas del estado de Hidalgo* (Azcué y Mancera and Fernández 1940–42) as one of the first examples of inventories in Latin America. On the same scale, the Argentine publication *Patrimonio arquitectónico y urbano de San Carlos de Bariloche* presented a series of recorded historical buildings classified in different typologies (Lolich 1991; 1995). *L’architecture au Yemen du Nord* presents a survey of numerous building types, their function, architectural shape, and decoration (Hirschi and Hirschi 1983). The *Architektur der Vergänglichkeit: Lehmbauten der Dritten Welt* (Wichmann and Adam 1983) displayed analyses and documentation on adobe architecture in Egypt, Mesopotamia, Iran, and Yemen; the Atlas, Sahara, and Niger regions of Africa; and the pueblos of New Mexico. Van Aerschot (1994) and the Proyecto de Cooperación Técnica Ecuatoriano-Belga presented an inventory that was used to inform planning decisions for the preservation of historic Quito, Ecuador.

With regard to large-scale documentation projects, which are much akin to inventories, there have been a number worth noting. Albery, Boccardo, and Spanò (2002) created a GIS for archaeological investigations at the Marchesato di Saluzzo in Italy. The GIS incorporated and correlated data that came from a variety of fields, including archaeology, geology, botany, history, and anthropology. The objectives were to reconstruct the site’s basic construction and to reveal the dynamics and use of environmental resources within the complex and articulated society that existed between the eleventh and fifteenth centuries.

Kölbl and colleagues (Kölbl et al. 2002) also used the GIS, but they used it in an urban environment. They presented an integrated inventory of historic monuments in the south of Morocco. The system was designed so that information could be easily recovered. Csaplovics, Herbig, and Börner (2002) created a chronological series of historical maps to analyze structures in urban and rural areas and to analyze changes in natural and cultural heritage sites at local to regional scales. Case studies for the mainly rural areas in the region of Lake Neusiedl (Austria and Hungary) and the town of Torgau, Germany, showed the efficiency of GIS-based approaches to topographic and chronological documentation. S. K. McIntosh (1994) presented the only inventory applied in West Africa. He suggested a radical redesign of inventory methods to ensure high-quality data and exchange of information among site managers.

Documentation has also advanced in the field of large-scale 3-D modeling for complex sites. The objective of historical virtual reconstructions is to facilitate site interpretation. Baturayoglu (2002) and Baturayoglu and colleagues (Baturayoglu et al. 2002) documented the Iron Age settlement of Kerkenes Dag, located in central Anatolia. Through the use of aerial photographs, global positioning system (GPS) topographical surveys, geophysical surveys, total station, architectural surveys with traditional methods, and photogrammetry, the team created a 3-D virtual model of the walls.

Despite these exemplary projects, few inventories have been sustainable over very long periods of time, because of changing needs, objectives, methodologies, and technology. Likewise, few efforts have integrated a range of professionals and fields of inquiry so as to effectively inform holistic planning and decision making. Furthermore, their application to earthen heritage has not, to date, created an accumulated body of knowledge that has broad applicability to earthen resources in general.

Historic Structure Reports: Condition Recording and Surveys

A host of manuals and articles have been published regarding ways to record the physical conditions of heritage sites and ways to design condition surveys and structure reports—notably the U.S. National Park Service's *Cultural Resources Management Guideline, NPS-28* (U.S. National Park Service 1985); *CRM Bulletin,* volume 13, number 4 (U.S. National Park Service 1990); the *Protocoles de vérification technique des bâtiments* of the Conseil National de Recherches du Canada (1993); the British Standards Institution's series on measuring buildings (1980); and Swallow, Watt, and Ashton's text on detailed survey methods (1993).

Specific to earthen architecture, Beas, Navarro Grau, and Maguiña (2000) presented the results of the Historic Structure Reports of five seventeenth-century earthen churches in the Oyón Valley in Peru. The architectural survey explains in detail the state of conservation of the churches, as well as their statements of significance, as a base document for future interventions. Hughes (2002) presented the preferred documentation methods for excavated vestiges at earthen sites. Matero and colleagues (Matero et al. 2000) presented new techniques of field and digital recording for the Casa Grande condition report, in an effort to design a protocol for condition survey for earthen sites. The article included a comprehensive glossary, as well as a manual and terminology, in order to improve the display of relevant information.

Despite the advance of digital technology for information management, relatively little research has focused on the application of the information for preservation interventions. Bryan (2002) explained the application of close-range photogrammetry for English Heritage conservation projects. Traditional survey techniques and photogrammetry were combined with 3-D laser scanning data for conservation projects at the standing stones of Stonehenge, the Whitby Headland area of North Yorkshire, and others. Blake (2002) described in detail how the same techniques applied by English Heritage were used for the documentation and interventions at the Iron Bridge, a symbol of the 1780s industrial revolution in Britain. Among the published literature, the application and implications of such evolving technology to earthen heritage are little mentioned.

Structural Reports: Recording and Monitoring

There has been a series of structural engineering conferences regarding the structural stabilization of earthen structures. The amount of material published is comprehensive, but only a few articles have dealt with historic buildings and have understood the significance of structural recording and monitoring as a fundamental piece for etiological building assessments. From the proceedings, it is important to point out *Stable-Unstable? Structural Consolidation of Ancient Buildings* (Lemaire and Van Balen 1988), as well as the *Report of the International Colloquium on Seismic Protection of Historic Buildings and Monuments* (Gülkan 1995), as two seminal publications that deal with methods for the structural recording, monitoring, and evaluation of historical buildings.

In the Lemaire and Van Balen publication, the article "The Use of Precision Electronic Monitoring Systems for the Analysis and Control of Structures" (Potter and Guant 1988) explains the reason for developing systems for the regular monitoring of movement in historic structures. The background of the experimental program, which took place predominantly in St. Paul's Cathedral in London, is given, along with an explanation of the results obtained and their possible interpretation. The experiments make it possible to state the significance of a monitoring plan for structural recording as part of the management of the site. In the same publication, Bähr (1988) and Carbonnell (1988) also explained the use of photogrammetry as a method of recording geometrical deformation of historical structures.

Though these are not specific to earthen structures, the methods are transferable.

Gülkan's *Report of the International Colloquium on Seismic Protection of Historic Buildings and Monuments* (1995) is based on the papers presented during a colloquium organized by the Getty Conservation Institute in Quito, and it includes a section dedicated to seismic hazard assessment as part of a comprehensive plan for the preservation of historic structures. At the time the colloquium was being prepared, the Getty Conservation Institute started a program called the Getty Seismic Adobe Project. This project produced three publications that are extremely important contributions to the field of earthen architectural conservation at the structural level for buildings located in seismic areas. The first of these publications (Tolles et al. 1996) had the primary intention of documenting the damage to historic adobe buildings caused by the 1994 Northridge earthquake.[2] The publication included the structural assessment of historic fabric affected by the earthquake, focusing on the recording of existing conditions, such as deterioration or structural changes that might affect the building's seismic performance. The secondary goal was to analyze the seismic performance of the buildings by assessing the nature of the damage, its cause and severity, and the effects of preexisting conditions on the performance. Such information would be essential to develop an accurate method for estimating the vulnerability of an earthen structure to seismic events. (For further discussion of seismic assessments, see "Earthen Structures: Assessing Seismic Damage, Performance, and Interventions," p. 69.)

Condition Assessments

A condition assessment goes beyond the work of a condition survey; it attempts to correlate conditions (physical, social, environmental, etc.), explicate deterioration processes, establish cause-effect relationships, and identify priority problems. This diagnostic function of condition assessments is a vital link in decision making about treatments; unfortunately, it is often lacking in conservation projects, and those at earthen sites are no exception. That said, some research regarding earthen heritage has explored this topic with an eye toward establishing more sound methodologies for recording, so as to inform diagnosis.

Crosby (1985) emphasizes the use of visual condition recording to further the understanding of the processes of deterioration and to identify treatments. Matero (1995) rationalizes the use of documentation for diagnosis, stabilization, interpretation, and maintenance of the lime plasters at Fort Union National Monument, an earthen site in New Mexico. Bishop and colleagues (Bishop et al. 1999) present the role of digital technology in the process of condition assessment of the Siqueiros mural *América Tropical* in Los Angeles. Eppich and Piqué (1999) explain the advantages of using digital recording to make information available during the process of monitoring and evaluation.

Hartzler and Oliver (2000) used past condition documentation to understand and quantify where, how, and why the adobe structures at Fort Union eroded. Their research focused on broad site issues of deterioration patterns and sequence, rather than on narrow concerns of localized deterioration. The condition assessment diagnosed those areas or fragments of the structure that were particularly vulnerable to deterioration and identified those parts that were critical to structural stability, thereby establishing a clear understanding of conditions in need of priority treatment.

Similar to the research at Fort Union, assessments at Casa Grande Ruins National Monument in Arizona (Matero et al. 2000) sought to explain deterioration and predict future changes using new field, laboratory, and digital recording techniques. The study was taken a step further when the data collected were manipulated using GIS software, in order to assess and prioritize future areas of treatments (Cancino Borge 2001).

Between 1985 and 1987, the National Park Service began a comprehensive survey program at Mesa Verde National Park, Colorado (Bohnert 1990). Initial steps included reviewing archival materials and thoroughly surveying extant plaster in eighteen cliff dwellings. Matero (1999) applied the same methodology used at Casa Grande and Fort Union to the conservation of earthen plasters in a pilot project at Mug House in Mesa Verde National Park, where the documentation strategy was designed as a model for future conservation efforts for alcove sites at Mesa Verde. Once the Mug House project was established as a model, the U.S. National Park Service initiated a priority treatment assessment of architectural finishes in selected excavated alcove sites. The National Park Service understood the role of documentation at different phases of the conservation program, and elaborated documentation strategies were applied and implemented. The condition assessment was

[2] Subsequent Getty Seismic Adobe Project publications addressed seismic interventions and guidelines for seismic retrofitting. See Tolles et al. 2000 and Tolles, Kimbro, and Ginell 2002.

derived from these surveys, through the use of appropriate digital technology and information management protocols (Matero 2003).

Digital technology has also contributed to the development of condition assessments by addressing the issues of site interpretation. Although it was not specifically designed for earthen structures, Stephani (1992) presented photogrammetry as the basic tool for recording. He explained how the generation of dense digital surfaces could be used for site condition evaluations through time. Maestri, Canciani, and Spadafora (2002) tested new computer software oriented to the reconstruction of 3-D models and graphics through nonmetric photographs that could be applied to the quantification of conditions of earthen finishes. The use of archaeological photogrammetry in rupestrian paintings at the Civil Cave in Castellón, Spain (Lerma 2002), used nondestructive methods to identify the primitive paintings and shapes. The procedure of image acquisition and classification offers new possibilities for data quantification and analysis. Finally, Smars, Van Balen, and Nuyts (2002) presented a computer program that builds 3-D models that are able to qualify and query data automatically. Information can be added, organized in themes, or linked to the model. The resulting database and the software's visualization capacities facilitate comparison, synthesis, and decision-making processes. Though these articles are tool oriented, they are important because of their impact on the management of information at different levels and scales of condition assessments.

Evaluation and Monitoring Assessments

In the past three decades, evaluation and monitoring have become essential components of any heritage management plan. Although evaluation and monitoring are not unique to the conservation of earthen sites, there have been a number of case studies applied to earthen constructions. In these case studies, standards have been designed in cases where documentation and recording have played an important role.

Regarding the evaluation of treatments, Lewin and Schwartzbaum (1985) reported the results of the long-term effectiveness of an ethyl silicate–based consolidant by comparing treated and untreated mud brick from the five-thousand-year-old mural paintings at Teleilat Chassul in Jordan. Chiari (1988) also presented a visual evaluation of the effects of ethyl silicate on the consolidation of mud brick from Huaca de la Luna in Peru, using scanning electron microscopy (SEM). Three years later, Chiari (1990) presented another evaluation case study on his work after twenty years at Tell ʻUmar in Iraq. Although the articles did not detail the design of an evaluation protocol for earthen materials, they described the significance of detailed archival information for evaluation purposes and the importance of evaluating treatments after they are completed.

Important evaluation research was also undertaken at Fort Selden, an earthen site in New Mexico, from 1985 to 1992. A field experiment using test walls was designed to assess certain treatments, so as to inform real-site interventions. Taylor (1988) presented the first report of mud brick test walls constructed to monitor the erosion rates of various amendments to mud plaster, the capillary rise in selected wall bases, and the impact of precipitation on wall caps. Agnew, Preusser, and Druzik (1988) presented a methodology for field testing, including standards for evaluation. These mud brick test walls were intended to monitor the impact of polyisocyanates and silanes as chemical preservatives, permeable aerotextiles for site shelters, geotextiles for drainage, and the use of composite synthetic fiber geobars as structural reinforcing elements. Although Taylor (1988) and Agnew, Preusser, and Druzik (1988) presented their case studies with the same evaluation purposes as Lewin and Schwartzbaum (1985) and later Chiari (1988), they delineated the evaluation protocol at an earlier stage and therefore collected relevant and measurable information at different steps of the program.

Years later, Selwitz, Coffman, and Agnew (1990) presented the results of the chemical preservative treatments, based on visual evaluation according to a numerical rating system. Agnew (1990) and Taylor (1990) detailed the protocol for monitoring the experiments using stereo photographic recording for the condition of the test walls, thermocouples, and a sixteen-channel datalogger system for the surface and interior temperature, as well as calibrated resistivity meter and preset pins for moisture monitoring.

The Chaco Backfill Research Project, conducted in Chaco Culture National Historical Park in New Mexico, USA (Dowdy and Taylor, 1993), is another example of documentation and recording designed for the purposes of evaluation and monitoring. The aim of this project was to assess the impact of backfilling on architectural features—namely, earthen components (wall and floor rendering and masonry units), stone, and wood. Selection of the five rooms to be included in the testing program, which involved removal of material from prior backfilling, relied heavily upon earlier notes and photographic documentation. This situation highlights the importance of having accurate and appropriate documentation of sites for future appraisal purposes. Chiari, Burger, and Salazar-Burger (2000) also presented a case study to evaluate the treatments of an adobe painted frieze in Cardal, Peru, that involved backfilling in 1988. In this case, there was no evaluation protocol, and the results were provided by visual examination.

Fiero, Matero, and Rivera (2000) presented a documentation protocol developed to address the condition assessment of plasters at Mug House in Mesa Verde National Park; this protocol was also used to evaluate the treatments applied a year earlier. The detailed graphic condition survey used vector drawings and allowed the conservator to go back to the site and quantify variations of different conditions.

Conclusions

Although heritage recording and documentation has developed into a specialized profession, relatively little research has focused on earthen structures and their distinctive conditions. Many recording technologies have been transferred and applied successfully to earth (e.g., wall painting methods applied to decorated earthen surfaces). However, there is a need to expand the body of literature related to the recording and documentation of earthen heritage, so as to build a basis for comparative study and replicability. In particular, while many site-specific projects have developed classifications of conditions, the field would greatly benefit from efforts to standardize nomenclature regarding earthen architecture and its forms of deterioration. In addition, because of the vulnerability of the material and the rapid deterioration process of an earthen site once it has been abandoned or excavated, there is the need to study and share rapid assessment techniques. Finally, a fair amount of research has been undertaken to monitor treatments; there is a fundamental need to design transferable protocols for the evaluation of past interventions and for the monitoring of sites.

The path to accurate and effective diagnosis and therefore to successful intervention programs begins with a thoughtful process involving explanatory recording, preferably executed over time. Only when a community begins systematically to record what it considers valuable—while also acknowledging that process as an act of continuous interpretation—will the field of preservation and conservation realize the potential of heritage recording as an analytical and planning tool, and as a method for improving the management of change.

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Deterioration and Pathology of Earthen Architecture

By Leslie Rainer

Introduction

For anyone familiar with earthen architecture, the deterioration of these structures is a constant preoccupation. While earth is one of the most widely used construction materials in the world, it is also one of the most vulnerable. Over time, declining expertise in traditional building techniques, lack of regular maintenance, and poor management of resources have led to the accelerated decay of a vast number of earthen structures, including archaeological remains, historic sites, and contemporary buildings. The heterogeneity of earthen materials and construction systems makes it difficult to categorize and characterize complex decay processes, so as to formulate a general conclusion regarding the problems and treatment of earthen structures. These factors combined put earthen architectural heritage at great risk. Referring to the deterioration of stone, Clifford Price aptly assesses this problem, which pertains to earth as well: “If we are to do anything to reduce or prevent this loss of our heritage, we must first be able to characterize the material. We need to be able to describe the decay, and to measure the extent and severity of decay. Only then can we hope to understand the causes and mechanisms of decay. Only then can we hope to understand the behavior of any particular (material) in a given environment” (Price 1996, 1).

The following is an overview of the research being carried out on the deterioration of earthen architecture. It covers the common symptoms, the identification and analysis of deterioration factors, and the causes of deterioration, drawing upon the literature from clay and soil science journals and agricultural studies, earth construction manuals, conservation conferences, and symposia that have been held over the past thirty years. While this overview attempts to analyze pathologies and decay factors methodologically, one must recognize that assessing deterioration is a circular question, one in which the symptoms are frequently the first visible manifestation of decay and the starting point for assessment. Often one must work backward to understand the source of a problem and to effectively design a response that eliminates causes rather than one that simply alleviates symptoms.

Methodologies of Assessment

In a paper on earth construction technologies appropriate to developing countries, R. E. Hughes (1986) addresses the question of the “restoration” and “maintenance” of earthen buildings, basing his views on a previous paper (Hughes 1983), which proposed a decay typology that takes into account the composition of the soils and their mechanical and chemical properties. Hughes stresses the need for an in-depth analysis of conditions that takes the following factors into account:

1. the environment on a macro and micro scale
2. the materials, again on a macro and micro level
3. the architectural form and its history
4. the building technique
5. the structural system
6. the use and reuse, such as foreseeable changes in the future

Hughes emphasizes that successful treatment relies fundamentally on characterizing and thoroughly understanding the processes that generate active deterioration and structural deformation. Repairing the visible evidence of damage without having addressed the mechanisms of the decay is of little value, and can it lead to more harm than good over time.

Van Balen (1990) goes a step further and presents a methodology for the conservation and restoration of earthen buildings, including the following elements:

- study of the physical environment
- study of the historical values
- condition of the building
- evaluation of the architectural typology
- architectural importance

Here he points out the importance of analyzing the value of the architectural object for conservation, and he attempts to go beyond purely technical and material considerations. This has been a trend in conservation philosophy over the past decades, and it is particularly pertinent for the conservation of earthen buildings.

General Pathologies and Deterioration Phenomena

General pathologies of earthen architecture typically tend to manifest at the top of the wall, where erosion occurs if the wall is not protected by an adequate roof or shelter, and at the bottom of the wall, if there is water penetration/infiltration, rising damp, and salts from the ground that may migrate into the wall at the base (CRATerre and Doat 1983). The causes of deterioration are often classified as intrinsic, when they can be associated with material composition or construction type, and extrinsic, when external factors such water, wind, and other environmental and contextual factors play a role.

A number of articles and papers have been written describing the general pathologies of earthen structures and decay phenomena. Houben and Guillaud (1994) describe some of the general pathologies, though with a focus on new construction, while Warren (1999) addresses agencies of failure and identification with a focus on historic structures. Crosby (1983) more specifically addresses deterioration of earth in the context of conservation. This paper provides a succinct summary of the most common types of deterioration and their primary causes. Crosby identifies the most common types of deterioration observed on adobe buildings and ruins as basal erosion, surface erosion, cracks and bulges, failure of the protective coating, upper wall displacement and leaning, and collapse. He then presents four water-related processes that cause deterioration: (1) wet/dry cycles; (2) freeze/thaw cycles; (3) capillary rise; and (4) condensation. (see section "Water" below).

With regard to more specific decay mechanisms, Odul (1990) states that a majority of phenomena of erosion are directly related to the actions of rain, wind, and human beings, and he describes all the symptoms and causes in detail. Viñuales (1981) and Chiari (1985) focus on water as the main cause of decay, and both make particular note of the link between water and the damaging effects of soluble salts. Olivier and Mesbah (1993) look at characterization of earth materials and also describe the most common causes of deterioration of earth building materials as water penetration, high water table, or use of impermeable plasters. Richard Hughes (1983) looks beyond material and environmental mechanisms and emphasizes structural decay mechanisms as well, including structural movements, shrinkage and cracking, moisture and thermal movement, density relaxation, and load redistribution.

A number of case studies also address deterioration, often with a site-specific focus but sometimes with indications of general deterioration factors that affect earthen architecture on a larger scale. Alessandrini and colleagues describe the materials and deterioration of the walls of Capo Soprano at Gela, in which they present the complex problems of deterioration by soluble salts, wind erosion, microbiological etching, and use of inappropriate materials in previous restorations (Alessandrini et al. 1990). Brown, Sandoval, and Orea (1990) discuss deterioration factors at the archaeological site of Paquimé, Casas Grande, Mexico, including water (rain, run-off, capillary action), wind abrasion, thermal expansion and contraction, and abrasion due to visitors. In an article on the earthen city walls of Grenada, Spain, Gallego Roca and colleagues note that the most deleterious agent in this case is the continual, often ad hoc, repair of the walls using incompatible materials (Gallego Roca et al. 1993). The use of cement has led to significant deterioration due to differences in thermal expansion and the presence of salts. Water is also shown to be a major factor, from flooding, causing deterioration at the base of the walls, and capillary rise, as well as rains, which lead to erosion along the top of the walls.

Analysis of Deterioration Processes

Condition recording is addressed in "Recording and Documentation of Earthen Architecture" by Claudia N. Cancino (p. 32). The following text discusses, in brief, the specific analysis of deterioration phenomena as a means of understanding processes of decay.

Few studies have been published that discuss measurement of the extent and/or rate of deterioration. One such study was carried out by Binda and colleagues, who conducted both accelerated aging tests in the laboratory and field tests to determine the rate of deterioration of different masonry walls—stone, mud brick, and mixed (Binda et al. 1995). Following the laboratory tests, full-scale models of facades were constructed, and they were subjected to moisture and salts. Data were collected regarding the environment, moisture and salt movements in the walls, deterioration of the external surfaces, the influence of mortar joints on moisture distribution, and the position and exposure of the material on the deterioration. In situ and laboratory results were compared in order to adjust the aging tests to the natural environment.

Other research projects have also used test walls to study the rate and extent of deterioration. One notable case is by Chiari, Rigoni, and Joffroy (1993), who set up two parallel testing projects at Fort Selden, New Mexico, and Grenoble, France, to evaluate the effects of ethyl silicate on earthen test walls. The direct results of this study showed that application of ethyl silicate on exposed earth walls slowed the deterioration process. The results were measured visually, and the darkening of the color of the surface was compared. Chiari et al. (1993) designed a method to measure differential darkening on sandstone using tristimulus colorimetry, which could be used for earthen walls as well.

Taylor (1988) describes another test wall project at Fort Selden that studied erosion rates of various amendments to mud plaster, capillary rise in walls, and impact of precipitation on wall caps by monitoring them over time. Selwitz, Coffman, and Agnew (1990) reported on the evaluation of the adobe test walls at Fort Selden for the effectiveness of specific treatment materials and methods of consolidation. In this study, the results were evaluated visually according to a numerical rating system.

Oliver and Hartzler (2000) undertook a thorough study for an archaeological site when they measured the deterioration of walls at Fort Union, New Mexico. In their study, they measured the loss of material and rate of erosion on wall elevations by looking at the change in wall area on elevations and sections, as well as examining deterioration of wall bases and wall tops. This work served to evaluate the stabilization measures for the site. The model developed for the work makes it applicable to similar sites, particularly earthen archaeological sites.

Regarding specific laboratory testing and analysis of deterioration products found in earthen building materials, it appears from the literature that most studies have focused on moisture and salts. As early as 1977, Clifton proposed that better methods be developed for characterization and nondestructive measurement of water content in earthen bricks (Clifton 1977). Since then, many studies have looked at this problem. Dayre and Kenmogne (1993) investigated the hygric properties of various earth test blocks and used gamma ray spectometry to study the granulometric differences between two earthen materials correlated with humidity transport. Using this method, they were able to determine the profile of the humidity front and to determine the hydraulic diffusivity of bricks made from clay soil on different structures.

Environmental scanning electron microscopy has been employed by Doehne (1995), and Doehne and Stulik (1990) to study the dynamic of wetting and drying of adobe samples and to evaluate their deterioration. Similarly, Rodríguez Navarro, Pardo, and Ginell (1996) looked at the swelling process in sepiolite-bearing Egyptian limestone sculptures using an environmental scanning electron microscope (ESEM), and they found that sepiolite could be, in part, a cause of ongoing deterioration. Although this paper deals with limestone, it could inform studies on deterioration factors in earthen materials. Basma et al. (1996) also looked at the swelling and shrinking of soils, and physical and microstructural changes due to cyclic swelling were studied, respectively, through ultrasonic investigation and observations with scanning electron microscopy (SEM). The results showed that cyclic swelling and shrinkage have a marked influence on the expansive behavior of clays. ESEM has also been used by Rao, Brinker, and Ross (1996) to study the weathering of stone—another example of the use of ESEM in the examination of material deterioration. ESEM is very useful in the study of salt deterioration as well, as discussed by Rodríguez Navarro and Doehne (1999), who concluded that different mechanisms of salt crystallization and saturation affect the deterioration of different materials. Again, while this study was conducted for stone, the analytical methods are relevant for earth as well.

Sparvoli, Ristori, and D'Acqui (1989) found evidence of microstructure modifications on soil samples equilibrated at different water potential, by mercury and nitrogen porosimetry measurements of the clay minerals and cements, again showing the effect of the composition of the soil on its behavior and showing its potential deterioration with exposure to water.

Specific Deterioration Factors

As stated above, one of the most deleterious elements for earthen materials is considered to be water, but it is generally the combination of many factors that prompts deterioration processes. The following looks at research specific to various factors, both intrinsic and extrinsic.

Building Materials and Construction

A fundamental intrinsic factor affecting the deterioration of earthen structures is construction typology and materials. Houben and Guillaud (1994) break down the building types and specific pathologies in their comprehensive handbook on earth construction. Given the different construction systems of earthen architecture, construction types can be generally categorized as:

Monolithic (or Massive Earth)

Excavated (*excavated* in this context means carved out of the soil, or troglodytic, as opposed to the archaeological sense of the word)

- excavated foundations
- excavated dwellings in deep loess deposits
- excavated chambers in volcanic tuff or conglomerate with sandy silt and clay lenses

poured earth
shaped earth
rammed earth (pisé)

Masonry

- adobe or mud bricks
- cut blocks
- stone/fired brick with mud mortar

Structural Component

- wattle and daub
- cob on posts

Often issues of intrinsic deterioration are specific to particular construction techniques. In excavated chambers, deterioration issues may be due to the materials in the soil layer itself, which might contain impurities that lead to salt efflorescence, biological growth, and so on. Pisé can show cracking at joints; adobe masonry may show deterioration if the bricks and mortar are not compatible or if there is a lack of sufficient keying between the masonry and plaster layer, leading to differential erosion. Wattle and daub may show deterioration of wood elements.

Studies on the deterioration of pisé have been conducted by Scarato (1986), CRATerre-EAG and others. Scarato's study is an analysis of the main characteristics of earthen heritage in the French regions of Rhône-Alpes and the Auvergne; a list of pathologies is also included (e.g., structural, such as deep cracks, and superficial, such as flaking, cracking, pests, etc.). CRATerre's study (1983) of "typical deterioration" in pisé structures in southern Morocco identified a recurring "water-drip system" that acts by impact, run-off, absorption, infiltration, and splash back.

Honeysett (1995) describes common causes of decay to cob, noting the following: (1) structural movement caused by forces applied to the wall from outside influences, (2) erosion and loss of material because of climate and the effect of fauna, and (3) the effects of humidity in cob.

Keefe, Watson, and Griffiths (2000) address the possible causes of failure in traditional cob buildings in England. The research suggests a correlation among geographical location, soil type, and the propensity to failure. Moreover, climatic factors, exposure, orientation, and wind-driven rain may be as significant as building condition and constructional details in promoting moisture-induced failure. In their work, they note that the use of inappropriate repair materials (cement plasters and repairs) has also led to the deterioration of cob buildings. Ziegert (2000) reports on cob buildings in certain areas of Germany, where cob was traditionally the most common method of building until the end of the nineteenth century. In his work, he examined construction technique, material composition, and types of damage and the causes. These two more recent studies look at construction techniques within the context of specific locations, considering the history of the building tradition and the influences of the surrounding environment in addition to the manifestations of decay. Such an orientation leads to a very localized study, but it ultimately results in a comprehensive and integrated approach that makes the research relevant and applicable to other contexts.

As early as 1970, Torraca published on the deterioration processes of mud brick structures (Torraca 1970). Other studies on the deterioration of adobe have been conducted largely in regard to adobe construction in the southwestern United States. The U.S. National Park Service, Preservation Assistance Division, Technical Preservation Services (1978), published a National Park Service Preservation Brief discussing the traditional materials and construction of adobe buildings and the causes of adobe deterioration.

A guide for the conservation of adobe architecture, published in 1998 by Cornerstones Community Partnerships (Uviña Contreras 1998), outlines the main processes of deterioration in adobe architecture in a very didactic format. In this guide, the authors make a distinction among three main deterioration processes linked to the actions of water and humidity:

1. The wet/dry cycle with three stages: (a) saturation of the wall through rain, (b) evaporation and migration of soluble salts in the outer surface, and (c) crystallization of these salts leading to surface erosion.
2. The freeze-thaw cycle, which also acts in three stages: (a) saturation of the wall by winter precipitation (rain, snow), (b) freezing of the accumulated humidity, causing (c) crystallization and expansion of the water.
3. Capillary rise and splash back at the base of the wall, resulting in deterioration by erosion. This deterioration may be accelerated and move toward the top of the wall when repairs are carried out with portland cement (fills or renders).

It is worth noting that while there are deterioration mechanisms specific to different building types and constructions, many of the causes of deterioration are common to all. The difference in construction technique between massive earth, masonry, or structural component systems plays a large part in how the building and the earthen materials react to the deterioration agent. In addition, it is not uncommon to find that deterioration results from the use of incompatible or faulty materials in the original construction. Houben and Guillaud (1994) stress the importance of using appropriate and compatible materials in their handbook on earth construction. Crosby (1980; 1983) specifically discusses this issue in relation to conservation in his research on the detachment of lime plaster from the adobe walls at Tumacacori National Monument.

Building Location

Building location can likewise be an intrinsic factor of deterioration of earthen structures. Pearson (1992) states that a dry site is essential because the absorbent nature of the material allows the walls to attract moisture by capillary action from the ground. Low moisture content in the wall is desired, and a well-drained, raised site is always preferable to a low-lying, damp one.

Building Evolution and Use

The evolution of an earthen structure and its past and current uses can beget a variety of intrinsic and extrinsic factors that influence deterioration. Very different challenges may affect historic buildings that are still inhabited, as opposed to archaeological sites where the remains of earthen structures have been exposed to the elements.

In historic buildings, the lack of maintenance and inappropriate repair materials are often cited in the literature as problematic. Koumas and Koumas (1993) make this point in describing the deterioration of medinas in Algeria. Michon (1987) attributes the decay of casbahs in southern Morocco to socioeconomic change that introduced new construction materials, and this is echoed in the publication by ICCROM, CRATerre-EAG, and UNESCO which discusses their work at the Royal Palaces of Abomey (Joffroy and Moriset 1996a; 1996b). Modifications of roofs, from steeply pitched thatch with a large overhang to shallow corrugated metal, result in poorly protected walls, decreased air circulation, and the creation of new stress points.

Deterioration factors for archaeological sites are often of a different nature, related more directly to abandonment and/or excavation. Most earthen structures in archaeological contexts have lost their roofs and are therefore all the more vulnerable to environmental factors of decay. According to Liégey (1990), excavation of walls is the cause of much deterioration. Modifications due to the constituent materials and internal structures of earthen walls, interfering with exterior phenomena and a sudden change of environment, lead to rapid deterioration. Structures that have long been buried have reached an equilibrium that is greatly disturbed at the time of excavation, when rapid drying of the materials can occur, and weight loads are suddenly shifted. Ndoro (1990) describes this as one of the main causes of deterioration of prehistoric daga structures in Zimbabwe. Macintosh (1974) studied the deterioration processes of earthen architecture in West Africa and investigated the current construction techniques to better understand the deterioration processes of pisé and wattle and daub in archaeological contexts.

Taking the topic further, French (1987) discusses the composition, properties, and deterioration of mud brick and the conservation of excavated mud brick structures. She identifies the main issues of mud brick conservation, including protection of the material after excavation, and proposes reburial and shelters as useful means of temporary or long-term protection for excavated archaeological structures. Palma Dias (1993) also gives an overview of the wide variety of causes of deterioration suffered by earthen archaeological structures that have been excavated.

For earthen archaeological structures that have not been in a buried state, exposure over time allows a range of deterioration factors to act upon the site and materials. Hartzler and Oliver (2000) describe the pattern and sequences of deterioration of Fort Union, New Mexico, an abandoned nineteenth-century U.S. Army frontier post made of adobe. They used current and historic documentation to compare conditions of the site over time and to better understand the mechanisms of decay, with the main factors identified as abandonment, exposure, wind, rain, and snow. Similarly, in their research on the conservation of mud brick structures in Abusir, Egypt, Šrámek and Losos (1990) note that rain and wind erosion contributed greatly to deterioration, and they carried out thermal analysis and thermogravimetry to show the difference in old versus new adobes.

Water

As noted previously, water is a common deterioration factor for earthen buildings. Numerous articles have been written on this topic, examining the problem from various aspects. Early on, Clifton (1977) noted that the deterioration of adobe structures can be directly or indirectly correlated with the presence of excess moisture, and he makes the point that the successful preservation of most historic adobe structures depends largely on effectively protecting these structures from water. Important studies by Chiari (1985) and Crosby (1983) describe the different problems that earth buildings face, including wet/dry cycling, coving at the base of walls from standing water, capillary rise, and surface condensation. Chiari, Rigoni, and Joffroy (1993) also investigated the problems of moisture with consolidation using ethyl silicate, building on this earlier work. Houben and Guillaud (1989) discuss the problems of water in earth buildings and provide useful diagrams, showing typical problems of moisture infiltration. Odul (1990) outlines the causes and effects of humidity in earthen walls and proposes an analytical schema and systematic approach to the diagnosis and treatment of these problems. His outline provides a comprehensive overview of the problems and serves as a useful tool for visualizing the causes and effects of deterioration.

In his work on the conservation of porous building materials, Torraca (1981) presents the scientific concepts underlying the conservation of materials such as stone, brick, and adobe. He discusses water movement in porous solids, masonry deterioration, and conservation. The U.S. National Park Service also addressed this issue in a preservation brief on the problems of moisture in masonry buildings (Smith 1986), another study that could relate to adobe buildings.

The United States Army Corps of Engineers Waterways Experiment Station Environmental Laboratory has published several articles in the *Archeological Sites Protection and Preservation Notebook* (U.S. Army Corps of Engineers, Waterways Experiment Station, Environmental Impact Research Program 1989) on the impact of water on earthen buildings, with Fort Hall National Historic Landmark (an archaeological site on the Snake River in Idaho) and the Rio Abajo District (a series of sites in the Central Rio Grande River Valley, New Mexico) as illustrative cases. Impacts that result in water-related changes include the grading of roads, vandalism through excavation and by means of bulldozer cuts, construction of irrigation canals, stream bank erosion, erosion control ditches, arroyo channeling, construction of houses and fences, maintenance of beehives, and use of livestock pens. This is one of the few published studies in which impacts to sites have been quantified, and it provides a good overview of the effects of waterways in proximity to earthen structures.

A range of additional case studies outlining water-related deterioration can also be found in the literature. Baggio and colleagues present a study of moisture migration in the walls of the church of Santa Maria dei Miracoli in Venice, where the walls have a high moisture content (Baggio et al. 1993). Through laboratory tests and field measurements, the thermal and hygrometric characteristics of the brick and stone were analyzed, and a numerical model of the heat and mass transfer was employed to study the drying of the walls. Dubus (1990) proposes electroosmosis to dry walls, using carbon fiber electrodes. Tests were conducted on samples of earth, with the intention of testing this method on an earthen archaeological site.

In a case study on the archaeological site of Mari, Syria, Bendakir and Vitoux (1993) discuss moisture problems in walls due to a high water table. In situ and laboratory testing were carried out to determine the moisture levels in the wall profiles. Bertagnin (1986) describes the deterioration of vernacular architecture in Algeria, where lack of maintenance has led to rain-related erosion of pisé, and extreme fluctuating temperatures and wet/dry cycling have spurred deterioration of mud brick structures in desert environments.

In another water-related study, Fouad (1993) investigated the damage to earth construction in marine environments, looking at the combined damaging effects of salt and water by airborne salts and moisture. Laboratory studies were carried out using a sea-fog simulator to reproduce the different effects of salt and water on compacted earth material. The study looked at treated (acrylic polymer) and untreated samples, then aging tests were performed. Garrecht, Hilsdorf, and Kropp (1991) also studied the effect of salt and water on structural elements of buildings (not necessarily earth). This study found that by capillary rise, hygroscopic salts are transported into the structural element of the building and influence the moisture behavior. He discusses the consequences of the moisture balance on salt-contaminated structural elements. In a final example, the influence of temperature and moisture content on the thermal properties of earthen buildings was investigated by Laurent (1990), who used a thermal shock probe to determine thermal parameters, heat conductivity, and heat capacity of earth walls.

While the effects of water on earthen structures are well documented in the literature, less research has focused on the actual decay processes associated with water. The research that has been undertaken relates primarily to the shrinking and swelling of clay particles with wetting and drying, and it applies more directly to soil or clay chemistry than to earth as a building material. Van Olphen (1977) gives an introduction to clay colloid chemistry and to the interaction of water and clay and how this leads to the swelling and shrinking of the clay particles. In this work he also presents a classification of clay minerals and examples of specific swelling mechanisms.

Newman (1984) addresses the role of clays in soil, within the context of agriculture. Here shrinking and swelling are correlated with clay mineralogy in the soil, in order to further understanding of the textural and structural modifications associated with wetting and drying. This model can be very useful when looking at earth mixtures used for construction. Osipov, Nguen, and Rumjantseva (1987) discuss the effects of cyclical wetting and drying and show that the more cycles of wetting and drying, the more swelling can be expected. Pardini and colleagues discuss more specifically "the structure and porosity of smectitic mudrocks as affected by experimental wetting-drying cycles and freezing-thawing cycles" and describe methods to obtain information on freeze/thaw and wet/dry cycles that affect structure and porosity (Pardini et al. 1996).

Prost and colleagues discuss the consequences of the hydration and the swelling-shrinking phenomena of clay (Prost et al. 1998). They investigate the state and location of the water on the clay particle surface, in order to understand adsorption and desorption of the clay particle. Rosenqvist's study (1984) on the importance of pore water chemistry on mechanical and engineering properties of clay soils shows how the changes in the soil chemistry due to moisture, salts, and other pollutants can change the properties of the clay structure, which can then affect the strength of the material. These scientific investigations, more closely related to earth as a building material, could be very useful to the conservation of earthen architecture.

Salts

Some research has been done on the problems of salts with specific application to earthen architecture, though most of the literature relates to salts in the context of stone conservation. Arnold has published extensively on salts, including the identification of salts on monuments (1984), salts in masonry (1981b), the nature and reactions of salts in walls (1981a), salts and stone weathering (1976), and rising damp and salts (1982). In other collaborative studies, he has investigated salt crystallization and salt efflorescence on walls (Arnold and Kueng 1985; Arnold and Zehnder 1985), weathering due to salts on monuments (Arnold and Zehnder 1990), and deterioration of stone materials in humid environments (Arnold and Zehnder 1988). Zehnder and Arnold (1988) also studied the damage from salt crystallization on wall paintings through laboratory experiments, which attempted to reproduce in situ deterioration processes. The experiments characterize relations between crystal habits, which are exhibited in efflorescence and substrate humidity. McGreevy (1982) discusses the effects of frost and salt weathering on limestone and points out that if there is a frequent and constant supply of salt, then rock breakdown will be enhanced; if the supply is limited and the amount remains constant, rock breakdown is inhibited. He concludes that further study is needed. While the aforementioned studies examine the presence of salts on stone buildings and monuments and related decay mechanisms, much can be applied to earthen architecture.

Additional salt research relating to bricks and other masonry has been done by Binda, Baronio, and Charola (1985). They analyzed the deterioration of brick by sodium chloride, sodium sulfate, and magnesium sulfate and conducted tests in different experimental conditions of humidity, temperature, and/or crystallizing time, to allow for crystal growth and varying degrees of hydration. Binda, Garavaglia, and Molina (1999) also propose physical and mathematical modeling of masonry deterioration due to salt crystallization. Charola and Koestler (1982) address the action of salt and water solutions in the deterioration of brick, and they find that the most deterioration results from mechanical damage produced by salt crystallizing in the pores of the brick. This remains quite relevant to the study of earth, which is similarly a very porous material.

In the literature that addresses salts and earth directly, the articles mostly relate to soils, including Blaser and Scherer (1969), who report on the expansion of soils containing sodium sulphate, and Ducloux and colleagues, who address salt efflorescence in soils in paddy fields in southern Niger (Ducloux et al. 1994). Zhang and Wang (1987) studied the crystallization characteristics in three saline soils in China and gave the order of crystallization and the morphology of each, studied by SEM. Fripiat, Letellier, and Levitz (1984) studied the depth of salt formation on clay and found that it was mostly on the surface. This may not be completely true for earthen building materials, which are more heterogeneous and porous than pure clays, and which swell with the introduction of surface water.

Little research has examined salts in the specific context of earthen architecture. Jerome (1993) presents a thorough analysis of mud bricks from the Bronze Age site of Palaiastro, Crete. The paper describes the presence of salts in the earth bricks and provides analytical protocols for analysis. Güntzel (1993) discusses the problems of saltpeter collection from earthen walls in the eighteenth century. While this is an anomalous case study, it is quite interesting, and points out the range of damage that can be caused by salt in earthen walls.

On a microscopic level, many studies have been done on the mechanisms of salt crystallization and deterioration effects. Perhaps the earliest work is by Correns (1949), who first studied the force of salt crystallization on stone. Winkler and Singer (1972) further investigated the disruption of stone and concrete by the pressure of salt crystallization against pore walls. Buil (1983) studied the thermodynamics of salt crystallization and proposed a new method for measuring salt crystallization pressure relevant to the deterioration of porous building materials. Pühringer and Weber (1990) conducted salt crystallization tests based on hydration pressure, with cycles of wetting, drying, and heating. Charola and Weber (1992) investigated the mechanism of deterioration by hydration and dehydration of sodium sulphate in building materials. Doehne (1994) made observations of the in situ dynamics of the same mechanism using the ESEM. In two studies specific to salts on wall paintings, Piqué, Dei, and Ferroni (1992) discuss the deliquescence of salts on wall paintings and state that much depends on the support and the environment, and Zehnder (1996) monitored the slow deterioration processes caused by crystallizing salts and gypsum efflorescence. Recent studies have pointed out the complex process of crystallization and deterioration, with different salts or combinations of salts present; this is an area warranting further study.

In the related scientific branch of soil science, research has been carried out on various aspects of salts and soil. Miller and Scifres (1988) reported on the effect of sodium nitrate and gypsum on the erosion of a highly weathered soil. Martín, Cuevas, and Leguey (2000) looked at the diffusion of soluble salts under a temperature gradient after the hydration of compacted bentonite; a testing method was outlined to determine the transport of different salts in compacted bentonite. While these studies may seem peripheral, the test methods used as well as the results could be applied to, and could advance, the field of conservation of earthen architecture.

Biodeterioration

In the area of biodeterioration of cultural heritage, one of the most comprehensive works is by Caneva, Nugari, and Salvadori (1991). This work explains the physiology of the primary biological agents of deterioration and correlates their activity with the specific environments that support their growth. Torraca discusses the problems of biodeterioration of porous building materials, pointing out the deleterious actions of fungi and bacteria (Torraca 1988). Another good reference, edited by Koestler (1991), presents a series of papers on the problems of biodeterioration of cultural property. The most useful is a bibliography by Koestler and Vedral (1991), which gives further references for study.

Chiari (1985) discusses the problems of biodeterioration in relation to earthen structures and discusses how algae, lichens, and higher plants can lead to root growth in walls, causing cracking of the earthen material. In his schema of deterioration factors, Odul (1990) notes plants, animals, and insects as causes of decay in earthen structures.

Weathering

Relatively little has been published that specifically addresses the weathering processes of earthen buildings and materials. Literature related to stone is much more common in this area. Given the vulnerability of earthen materials to erosion and weathering, further research should be carried out, with an eye toward developing preventive conservation measures.

A comprehensive work on weathering is by Yatsu (1988), *The Nature of Weathering: An Introduction*. While this work focuses on stone and is not specific to earth, the work can be applied to study weathering of earthen materials. Physical weathering due to swelling and shrinking of clay minerals is studied in detail, as is salt crystallization. Mineral transformation in the weathering zone is also studied, showing how physical, chemical, and biological decay processes act together.

In a case study on the conservation of the earthen site of Chan Chan, Morales Gamarra (1985) describes processes of deterioration, attributing much to climate and topography. Chan Chan is located near the sea, in an area where there is wind erosion combined with airborne and waterborne salts. The soil has little clay and is rich in salts. The exposure of the site, combined with diurnal and seasonal temperature and humidity fluctuations, leads to persistent weathering and erosion of exposed walls and other architectural elements.

Crosby (1988) maintains that the weathering of adobe is related to moisture, the expansion of soluble salts with moisture, and wetting and drying cycles. The study conducted by Brown, Clifton, and Robbins (1978) is a good scientific example of this theory. They carried out analysis on adobe samples from three historic structures to determine mineral assemblage, particle size distribution, soluble salt content, and porosity. The data were correlated with observed weathering of the structures, and soluble salts were seen to be the primary cause of deterioration of the adobes from one site. This early study is exemplary of the use of microscopic analysis and macroscopic observation both to determine deterioration mechanisms and to correlate them to historic earthen structures exhibiting weathering. Similarly, Helmi (1990) reports on the chemical weathering, by water and salts, of mud brick in Egypt, with an emphasis on treatment testing of consolidant materials.

Perhaps the most pertinent research regarding the weathering of an abandoned adobe site is by Hartzler and Oliver (2000), in which they studied the patterns and sequences of deterioration by wind, rain, and snow. This, combined with a study of the history of construction, led to a comprehensive preservation plan for the site.

Atmosphere (Pollution)

As with weathering, there is limited literature addressing the deterioration of earthen architecture due to atmospheric factors, such as pollution. Schaffer (1967) addresses the effects of air pollution on porous building materials, describing the chemical and physical processes of deterioration, particularly related to stone and brick. The damaging effect of acid rain on archaeological remains is discussed by Scharff (1990), though again, not specifically in relation to earth. Torraca (1976) points out that air pollution causes a modification of deterioration processes that often results in an increased rate of attack, or in the decay of materials that are otherwise weather-resistant in nonpolluted environments.

Human Activity

The use of cultural heritage resources involves a range of human activity, from visitation to conservation treatments. While many human actions may be well intended, Alva Balderrama and Chiari (1984) note that ill-planned and improperly researched interventions can have deleterious effects. This situation is often pronounced with earthen architecture, as the loss of traditional know-how about building with earth and the limited research regarding its behavior in construction may result in ad hoc responses to problems.

Abrasive wear and tear due to visitation is a common problem among all heritage resources, and earthen sites are no exception. While this is a known factor of deterioration, little research has been done regarding the impact of abrasive wear and tear on earth. One exception is the work by Brown, Sandoval, and Orea (1990) that looked at visitor impact at the earthen archaeological site of Paquimé, Mexico.

Another common cause of deterioration is the lack of monitoring and maintenance of both inhabited buildings and archaeological sites. The nature of earthen materials makes regular upkeep critical. This is mentioned throughout the literature; however, it is stressed in only a few texts and has not been the subject of systematic research. One notable exception is the work by Oliver and Hartzler (2000), whose study of deterioration patterns at Fort Union clearly correlated a lack of maintenance, as well as abandonment, with the decay of the site.

The use of inappropriate repair or treatment materials and the poor design of interventions remain endemic to earthen architecture, and they are frequently mentioned in the literature. Treatment of such structures has all too often been carried out without a full understanding of the sensitive nature of earth or of the incompatibility of many common repair materials (especially cement), as noted by Pearson (1992). Some case studies deal explicitly with the use of inappropriate repair materials, such as the church of Nossa Senhora do Rosario, Embu, São Paulo, Brazil. In this study, Pecoraro (1993) notes that, while the main decay factor was water, deterioration was exacerbated by the use of cement. Another case addressing earthen architecture in Argentina cited the poor design of a new roof as the primary cause of degredation. This same point has been made about the Royal Palaces of Abomey, in a report published by ICCROM, CRATerre-EAG, and UNESCO (Joffroy and Moriset 1996a), where the use of inappropriate roofing and repair materials has led to accelerated deterioration.

Fundamentally, poor planning and poor management of conservation efforts will have negative effects on any resource. Integrated efforts that consider conservation needs within a broad context of site considerations are the surest way to check deterioration and ensure long-term preservation.

Conclusions

The general factors causing deterioration of earthen architecture, for the most part, were investigated and defined in the literature from the 1970s and 1980s. These findings provided a foundation for more in-depth study of the mechanisms by which they work. Later research has focused more specifically on the correlation between causes and symptoms of deterioration, leading to a more complex understanding of material and structural behavior. Advances in scientific equipment and research protocols have greatly aided the analysis of earthen materials and deterioration products and mechanisms. What remains critical is the forging of a stronger link between field studies and laboratory analysis, which ultimately requires greater focus on the fundamental differences between new and historic/aged earthen materials. Much of the research being carried out today should be brought to the field to study the mechanisms of deterioration in situ, outside of the controlled laboratory environment. If this is done, the caliber of scientific research would serve the field conservator well, and the field conservator could bring actual site conservation problems to the scientific realm for further study.

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Moisture Monitoring in Earthen Structures

By Brian V. Ridout

Most of the organisms associated with damage to earthen structures are dependent on elevated moisture content in the walls. This moisture is required for the survival of the plant or animal, but it may also soften the construction and make it more accessible as a habitat. The identification of damp wall areas and the quantification of moisture contents are therefore of considerable importance. Unfortunately, most of the efforts to develop handheld moisture monitoring devices for building materials have been directed at wood and concrete. Instruments for the convenient and nondestructive measurement of moisture contents in walls have proved difficult to devise. Trotman (1991) provided a specification for the "ideal" method, and the requirements he listed provide useful category headings for this overview.

Nondestructive Methods

A nondestructive technique is one that measures some property of the material that varies with moisture content, rather than measuring the absolute moisture content of the material itself. It will be an indirect technique that does not require the removal of material from the wall.

One problem with an entirely nondestructive method is that walls are usually rather thick, and any equipment that will measure more than surface or near-surface properties is likely to be inconvenient in some way. Thus, impulse radar or infrared thermography will each provide useful information, but both types of equipment are prodigiously expensive, and the results require considerable experience to interpret. Binda, Colla, and Forde (1994) and Forde and colleagues (Forde et al. 1993) showed that digital impulse radar is able to differentiate between saturated, partially saturated, and unsaturated areas of wall, while Dill (2000) stated that the method measures variations in moisture contents rather than absolute values. Calibration by some other method is essential. Demaus (2001) and Mill (1981) state that infrared thermography can show moisture gradients, and these are inferred from variations in heat radiating from wall surfaces. Infrared thermography is sometimes particularly useful because it only requires remote access, and results may be obtained immediately from large surface areas. Surveys may, however, have to be planned around weather or time of day in order to obtain a suitable temperature gradient, and the differences measured may prove to have more than one possible physical cause. Both methods are essentially comparative, and neither gives a measure of absolute moisture content.

Some other methods are nondestructive but only measure moisture trends or have limited field application. These would include gamma rays and neutron scattering (Wormald and Britch 1969; De Frietas, Abrantes, and Crausse 1996), neutron radiography (Justnes, Bryhn-Ingebrigtsen, and Rosvold 1994), and nuclear magnetic resonance spectroscopy (Gummerson et al. 1979; Krus and Kiessl 1989; Carpenter et al. 1993).

Apparatus using neutron scattering (nuclear moisture gauge) is available for measuring moisture trends in flat roofs and floors. It might be used on walls, provided that some form of mounting rig were assembled that would hold the apparatus flat against the wall surface (Dill 2000). The method is unlikely to be convenient in most situations.

Moisture meters that nondestructively measure the dielectric properties of porous materials with electromagnetic waves (capacitance meters) are commercially available, but the results only relate to the surface layers. Jazayeri and Ahmet (1998; 2000) have shown that the depths to which the electromagnetic waves reach (scanning depth) can be increased in wood by a greater separation of electrodes. This may be an interesting topic for investigation with other building materials, but capacitance meters still need to be calibrated (Milota 1994), and other limitations are discussed in the following sections of this overview.

Bogle, McMullan, and Morgan (1983) devised a capacitance meter for use on walls by connecting a capacitance in parallel with a resonant LC circuit detuning it. The degree of detuning was a measure of capacitance, which in turn was a measure of moisture content. This method was claimed to cause minimal interference with the wall.

Eller and Denoth (1996) devised a capacitance soil sensor with a fork-like geometry, which gave results comparable to those of other commonly used methods. This may prove useful on earth walls.

Finally, Phillipson (1996) referenced and discussed two older ideas that have been explored somewhat with modern technology. These were infrared absorption (Cornell and Coote 1972) and microwave absorption (Watson 1965; 1970). Both require calibration. Bilborough (1970) investigated microwave absorption for measuring the moisture content of wood. Trotman (1991) discussed the use of microwaves and stated that a good correlation between microwave attenuation and moisture content could be obtained with careful calibration in homogeneous materials. He noted, however, that results from nonhomogeneous materials (e.g., bricks and mortar) had proved disappointing. Belsher (1979) used a microwave system to determine various characteristics, including moisture content, in mud brick walls, and obtained favorable results.

A handheld instrument has recently become available in the United Kingdom for measuring the moisture contents of concrete, sand, and gravel (Assenheim 1993; Dill 2000), and the manufacturers believe that this meter will be appropriate for general use on walls. This meter works by measuring the dielectric constant of the material in the same fashion as a capacitance meter. The higher frequency of electromagnetic waves used is said to make the instrument less susceptible to impurities such as salts (see "Effects of Salts" below).

Moisture Monitoring and Substrate Type

Measurement of moisture in walls, independent of substrate type, is not achievable at the present time with any convenient instrument, if accurate readings are required. Surface or shallow subsurface moisture contents can be obtained with handheld meters using probes that cause minimal damage, and the most popular type is undoubtedly the resistance meter. This meter measures the electrical resistance between two metal pins that are pressed firmly into the surface. If the meter is used on wood, moisture content is read directly from the calibrated scale because it is possible to derive a linear relationship between resistivity and wood moisture content over a useful range (typically 9% to about 28%). Even with timber, however, the meters produce difficulties, and Hall (1994) found that six readily available European moisture meters produced timber moisture content equivalent readings of from 13.5% to 16% when tested against the same resister. Ahmet (1994) investigated the problem and found that the meters were accurately measuring resistance but that there were no internationally agreed-upon calibrations. This is not entirely surprising because Ahmet and colleagues (1999) have shown that equilibrium moisture contents for a given species of timber can be naturally variable and can also be dependant on the way in which the timber dried. Calibration tables are therefore likely to vary according to the particular planks of wood against which the meter was tested at any particular humidity.

The situation is far worse with masonry moisture content readings, because the meters in common use are not calibrated against the immensely variable masonry materials (Howell 1996), and readings are just a reference scale. False readings may also be produced by condensation (Cheetham and Howard 1999), salts (see "Effects of Salts" below), and concealed conductants—e.g., foil-backed plasterboard (Melville 1992). Nevertheless, the pattern of multiple readings can perhaps sometimes be more informative than absolute moisture contents (Coleman 1997).

Resistance meters may be less accurate than capacitance meters, at least in wood (Kemmsies 1998; Wilson 1999), although Carter and Ahmet (2001) found considerable variation in a comparison test between the two types of meters. Capacitance meters do have the advantage that they measure moisture contents to a depth of a few millimeters without leaving pin marks in the surface.

Moisture Monitoring and Substrate Textures

Commercial capacitance instruments for the building industry in the United Kingdom may give spurious readings on rough surfaces, and the measuring head may be damaged if it is delicate (Dill 2000). Morgan, Wood, and Holmes (1993) had a similar problem using capacitance meters on soil surfaces, and they found that altering the size and protrusion of the electrodes improved measurement repeatability.

Resistance moisture meter probes are largely independent of surface texture but leave needle marks in the surface, and the readings are superficial. Surface readings may be confused by condensation. Deeper readings may be obtained if the idea of total nondestructibility is compromised and small holes are drilled. Several resistance meter manufacturers supply long probes that are insulated, except at the tips, and these are inserted into paired and predrilled holes. The contact between probes and wall is, however, strongly influenced by the pressure applied (Trotman 1991), so that consistent and meaningful readings can be difficult to obtain. A second significant problem is that walls are rarely homogeneous, so results may be difficult to interpret.

The last two problems were addressed during the first half of the twentieth century by the Salter gauge, which was originally developed in 1940 for use in soils (Trotman 1991). A helical coiled electrode surrounded a straight electrode, and the assemblage was then placed in a predrilled hole within the material or structure to be tested. Contact between wall and electrodes was made by filling the hole with plaster of paris, and the latter also acted as a single reference material when it had equilibrated with the surrounding structure. Unfortunately, distribution of water between the plaster and test material is dependent on the pore size distribution of the test material, as well as on its moisture content. Calibration curves have therefore to be obtained (Trotman 1991).

Hudec, MacInnis, and Moukwa (1986) devised a measuring method for use in concrete that they called "capacitance effect." This method involved applying a constant electric field (voltage) between two embedded steel electrodes and measuring the resulting current at two frequencies, from which a change in capacitance, and therefore in moisture content, could be calculated.

Resistance methods devised for soils may be relevant to earth walls, and Amer et al. (1994) tested a fiberglass soil-moisture electrical resistance sensor against the gravimetric sampling method (see "Calibration versus Destruction" below). They concluded that the method was reasonably accurate in some situations.

Calibration versus Destruction

If the concept of nondestruction is abandoned and small holes in the wall are allowed, then calibration ceases to be necessary. Incremental samples can be taken from within the wall, and their absolute moisture contents can be established gravimetrically by the oven/balance method (Building Research Establishment 1975; 1986). Samples are wet-weighed, dried, and then weighed again, so that water loss can be given as a percentage of a dry weight. Normally a temperature of 105°C is used, but this must be reduced to less than 40°C if there is plaster or salt laden material present (Dill 2000). The method has been standardized as RILEM recommendation MS-D.10 (de Vekey 1997). The technique requires an oven and a balance; samples must be taken to a laboratory, and it cannot be considered a true "field" method. Site-based field drying methods have been devised using warm-air drying units, microwave ovens, and infrared heaters, but uncontrolled drying can cause numerous problems, both with the sample and with the equipment (Dill 2000).

The problem of portability has been overcome by reacting the wet sample with calcium carbide and measuring the pressure generated by the acetylene gas evolved (Building Research Establishment 1986). Commercially available meters work by mixing a fixed weight of powdered test material with a fixed volume of carbide in a pressure cylinder. The cylinder is fitted with a manometer that is calibrated as percentage moisture content. Carbide meters indicate available water and are therefore largely independent of the type of test material provided. It is up to the user to decide whether 7% moisture content, for example, means that the test material is dry, damp, or wet, and the removal of a calibration sample from a definitely dry section of wall may be useful. The main disadvantages with these meters, in this author's experience, are the disposal of waste carbide and the illegality of taking carbide on aircraft.

Gravimetric analysis and carbide meters assess the moisture contents of samples that have been removed from the wall and are therefore not replicable if repeated moisture content evaluation over time is required. Samples taken at frequent intervals to monitor drying, for example, will leave a wall full of holes and will be subject to substantial sample variation.

The Building Research Establishment eliminated the need for calibration and introduced repeatability by a method that required the removal of a 25 mm core from the wall (Building Research Establishment 1975). This was then fitted with a rubber sleeve at each end and reinserted. The core could be removed at intervals for weighing, and the dry weight could be calculated by drying the core when the series of readings had been completed.

Two further methods have been devised that are worth consideration. The first of these is an old method devised by Vos and Erkelens (1958), who developed a wall probe with several thermocouples on the surface and a heating element in its core. This device worked on the principle that thermal conductivity increases with moisture content. The major problem encountered seems to have been that extraneous heat sources (e.g., sunlight on the wall) could distort the readings. Vos (1965) overcame this problem by using a second probe installed some distance away to measure normal wall temperatures. Vos (1970) reviewed the development of the thermal conductivity probe and concluded that it was more difficult to use when walls were nonhomogeneous or constructed from materials with a low thermal conductivity. Nevertheless, Newman (1974) found that the probe could be accurate, and the idea might be worth investigation with modern technology.

Sell (1985) described a system that had been developed in Switzerland for calculating equilibrium wood moisture contents from the relative humidity within holes drilled into wooden components or walls. This method was devised as a means of continuous monitoring because it was felt that a humid or salt-rich environment would corrode conventional electrodes. Equilibrium moisture contents for timber were then calculated from an equation devised by Simpson (1971). Humidity probes are also inserted into holes in walls, or sealed into surface-mounted chambers (Dill 2000). These methods have been particularly popular for assessing the dryness of newly constructed cementitious bases or screeds.

The idea of direct humidity measurements in walls has become generally popular, at least in the United Kingdom, for monitoring drying following flood damage. Unfortunately, there is a tendency to rely on relative humidity readings alone, without taking into account temperature. The results obtained are substantially misleading, because there is an inverse relationship between temperature and humidity, so that quite dry air can have a high humidity if the temperature is low. The way to avoid this mistake is to convert temperature/humidity readings into air moisture contents (absolute humidity, Thomson 1986).

The necessity to convert humidity data can be avoided by equilibrating a sensor with known characteristics in a cavity within the test material, and wood has proved to be useful for this purpose. Dill (2000) described a wooden plug sleeved with polyethylene that was inserted into a hole drilled into the material to be tested. The sleeve prevented the sensor from touching the sides of the hole, and the hole was plugged over the sensor in order to prevent air exchange. The sensor was interrogated with a resistance-type moisture meter. Similar methods have been devised for measuring the moisture contents of wood using wooden probes fitted with electrodes. Forrer and Vermaas (1987), TenWolde and Courville (1985), and Carll and TenWolde (1996) have described recent versions. Dai and Ahmet (2001) tested these sensors and found the first (Forrer and Vermaas) to be complex and expensive to make, while the other two produced difficulties with electrical contact between wood and electrodes and were prone to significant intersensor variation. Dai and Ahmet (2001) therefore produced their own version, which they believe overcame these difficulties. Their sensor is for use in timber or in walls.

Effects of Salts

A major reason that wooden wall sensors are isolated from the sides of the hole into which they are inserted is to prevent the uptake of salt laden water, which would alter the electrical resistivity of the sensor. Salt contamination from groundwater, or from the wall material itself, has been a constant problem in the development of many types of moisture meters (Trotman 1991). These salts may be mobilized by water movement within a wall, and the incautious investigator, with a resistance or capacitance moisture meter, might conclude that there was a significant damp problem when only a small amount of water was present. Trotman (1991) investigated the effects of salt solutions and found that a weak solution of sodium chloride or a saturated solution of calcium sulphate had little effect on resistivity. A 0.5 M solution of sodium chloride, however, produced a reading on a resistance meter reference scale of between 80% and 90% when the actual moisture content was anywhere between 5% and 22%. Ridout (2000) avoided the salt problem with wooden wall sensors by assessing their moisture contents gravimetrically with the oven/balance method. This method simplified the sensor design because it allowed direct uptake of moisture, and the sensors therefore needed only to be rods inserted into holes drilled into the wall. Sensors could be replaced and the same holes reused at the end of each monitoring period; the method has proved particularly useful for measuring the rates of drying in walls following fire damage. It also provides good moisture profiles from the thickness of the wall. No claim is made for precision measurements, but the methodology is consistent, and the overriding considerations for its use have been simplicity and the significant loss of sensors on building sites or wherever there is public access.

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Earthen Structures: Assessing Seismic Damage, Performance, and Interventions

By Frederick A. Webster

The review of the available research literature found that there are three main categories of research related to seismic deterioration/pathology and seismic intervention in earthen architecture. These categories are field observations, testing, and analysis. It was found that, whereas there is only a limited amount of research that directly relates to adobe and earthen materials, much effort has been spent on seismic behavior and seismic intervention into historic stone and brick structures. Many of the recent innovations that have related to mitigating earthquake damage to historic masonry structures have focused on stone and brick churches in Europe. However, it is clear that many of the analytical techniques and seismic interventions could be applied to earthen architecture.

Field Observations

Damage Patterns of URM Structures

Field observations of earthquake damage to earthen architecture are often part of a much larger effort to observe and record damage to all sorts of man-made structures, as well as natural geologic phenomena. The Earthquake Engineering Research Institute, for example, sponsors teams of engineers, seismologists, public policy experts, and others to make reconnaissance efforts to areas affected by earthquakes immediately following an event. These teams work with local authorities and professionals to collect a limited amount of damage data before it is destroyed by recovery efforts, as well as to report it to the broader engineering community in a timely fashion. At times a small subteam will focus on the performance of unreinforced masonry (URM) structures (e.g., Holmes and Lizundia 1990), possibly including adobe and other earthen buildings in their findings, but there are very few relevant data that can further understanding of the behavior of these buildings. The content and quality of this reporting vary from event to event.

Erdik and Gulkan (1993) compiled a report on the Erzincan, Turkey, Earthquake of 1992, including a reasonable amount of useful information regarding low-strength unreinforced masonry structures in and around Erzincan. While a number of URM buildings in the Erzincan earthquake did suffer severe damage and/or collapse, a large percentage performed well. This performance can be attributed to the small sizes and good configurations of these buildings, which resulted in acceptable demands on the lateral-force resisting system. The majority of URMs in Erzincan and the surrounding villages are one- or two-story residential buildings with reinforced concrete flat slab floors supported by the masonry walls. The exterior elevations generally have small, widely spaced openings. The relatively solid walls with few and small openings resulted in redundant force resisting systems with relatively high strength.

A number of buildings under construction in the village of Uzumlu, twenty miles from Erzincan, suffered severe damage or collapse. Six of forty two-story residential structures suffered severe damage, including collapse of the lower story. Examination of the damaged masonry walls indicated that they were constructed with cellular clay blocks with little compressive strength. The added force resulting from the earthquake caused them to delaminate. The same contractor, who apparently was trying to cut costs by using an inferior hollow clay block, built all of these buildings. Another contractor constructed all the other houses in the development, and the block used was a solid block with small circular holes. The structures built with these units were able to withstand the severe diagonal cracking without collapse. Quality of construction practices and the type of masonry, therefore, appear to be important contributors to the performance of these buildings in earthquakes.

The performance of small adobe and low-quality mud brick constructions varied from no damage to collapse. Within any specific area, the performance of these buildings depended on a number of parameters, including wall thickness, roof mass, size of rooms, and quality of materials. It also appeared that the wide variation in the performance of these buildings could be attributed to the local soil conditions and to the effects of soft soils near the river basin. Unfortunately, soon after the earthquake, a few villagers were seen rebuilding their adobes with the same materials and techniques as before.

Sometimes a more extensive reconnaissance effort will be conducted on a specific type of building (e.g., historic earthen buildings), in which case it is sometimes possible to use the collected data to develop information on expected damage levels of similar buildings in future earthquakes. Tolles et al. (1996) conducted a damage survey of nineteen historic adobes in the Los Angeles area following the devastating Northridge earthquake of 1994. Seismic performance at both the macro and micro levels was evaluated. Types of damage were categorized, and an overall damage level was assigned to each building.

Performance of Strengthened URM Structures

In some field observation reports, the performance of URM buildings that have been previously retrofitted is examined following an event. Following the October 1987 Whittier Narrows earthquake in California, Deppe (1988) analyzed damage to unstrengthened as well as strengthened and tension-anchored-only buildings in Los Angeles and attempted to determine the most effective ways of improving the design standards for strengthening URMs. Moore and colleagues (Moore et al. 1988) presented preliminary case studies on buildings that had been rehabilitated to conform to the Los Angeles hazard reduction ordinance. It was found that both rehabilitated and nonstrengthened buildings suffered damage due to separation of the outer wythe of brick, out-of-plane bending failure, and/or in-plane shear failures of wall piers, especially at building corners. A few of the buildings reported on by Tolles and colleagues (Tolles et al. 1996) had seismic interventions in place prior to the Northridge earthquake. The observation was that at low levels of shaking intensity, the interventions did not affect the behavior noticeably. However, at higher levels of ground shaking, the damage levels were observed to be lower than the expected damage level for those buildings with no seismic intervention. This appears to be a similar conclusion to that observed in shake table laboratory tests on stone and brick masonry model buildings in Italy (Benedetti, Carydis, and Pezzoli 1998). This subject will be discussed below in the section on testing, under the heading "Specific Seismic Intervention Development."

Performance Based on "Seismic Culture"

Of historical and cultural interest is the evolution of seismic interventions and construction techniques, which address the concern of earthquake damage to low-strength masonry buildings. Erdik and Gulkan (1993) to a certain extent allude to the traditional practice of building masonry residences that are regular in shape, are only one or two stories in height, have flat concrete slab floors supported by the walls, and have walls with only small, widely spaced openings. Although the contractors building these residences may not be aware of it, this is an example of a "seismic culture" influencing the design of these structures. Arya (2000) also provides a set of interventions and design recommendations based on traditional methods of nonengineered masonry construction, including predisaster mitigation and preparedness and damage reduction initiatives through building codes and guidelines.

Tobriner (1984) provides a history of the development, from 1755 to 1907, of reinforced masonry construction designed to resist earthquakes. The early history of the invention of earthquake-related reinforcement techniques is important. This paper focuses on the most basic types of reinforcement: vertical, diagonal, and horizontal wooden and metal members attached to or embedded in walls of mortared masonry.

According to the paper, the first recorded reinforcing method for masonry buildings occurred following the earthquake of November 1, 1755, in Portugal. Engineers devised an internal wooden cage, called the *gaiola* (jail), to be incorporated into each new building. The cage is cross braced and designed with staggered lintel heights. This system was used in Portugal until the 1920s. Unfortunately, there is no documentation regarding the success of the *gaiola* system in actual earthquakes. The system was little publicized and does not seem to have been known in other countries.

Following a series of devastating earthquakes in Italy in 1783, a solution similar to the *gaiola* and called *la casa baraccata* was developed to tie together masonry buildings by means of an internal wooden framework. In addition, the concepts of continuous foundation, symmetrical plan, and redundancy were introduced. While the *casa baraccata* fell into disuse in the late nineteenth century, it proved to be a viable life-saving system during the catastrophic earthquake of 1908.

Building laws for the reconstruction of Reggio Calabria were stipulated in 1784. In addition to wooden supports embedded in the masonry, iron bars must also be strung through them. Although this had been stipulated, no iron was found to be present following the 1908 earthquake. Iron hoop reinforcing was discovered in England in 1825 as a means of reinforcing brick walls. Southern Italy was the first place to adopt widespread use of iron for earthquake resistant construction following strong temblors in 1854. Tie rods at each floor level were put into tension by being heated and cinched down; then they were connected to the next story by iron straps.

In spite of severe earthquakes in 1865 and 1868, no widespread attempts were made to improve the construction practices in San Francisco. Brick buildings were vulnerable to damage, but if they were built well and on hard ground, it was thought that they could easily survive an earthquake. Although there was no concerted effort to develop earthquake resistant construction practices in San Francisco, the 1868 earthquake stimulated experimental masonry construction methods. One was based on bracing walls by vertical rods or plates and anchors passing through them. The several walls are united and bound by horizontal tie-rods secured to vertical plates at the corners.

In another instance, the Palace Hotel in San Francisco was designed to be both earthquake proof and fireproof. The walls were on average two feet thick, with cement rather than lime mortar, and iron bars were imbedded every four feet in the bricks along an entire course of a wall. Yet despite the excellent performance of this building in the 1906 earthquake, little change in design and construction practices for brick buildings was seen until after a couple more devastating earthquakes. Although the technology was available and relatively inexpensive, earthquake resistant masonry construction only came of age after the lessons of the 1906 earthquake were repeated in the Santa Barbara, California, earthquake of 1925 and the Long Beach, California, earthquake of 1933. These two events, along with a growing awareness of the structural and economic value of reinforced masonry, finally popularized reinforcement.

Testing

Laboratory testing of wall specimens and scale models of buildings is an effective means of developing innovative seismic interventions, as well as a means of studying the behavior and damage patterns of unreinforced buildings. Testing research can therefore be separated into two distinct subtopics related to earthquake performance: (1) the study of building parameters in relation to performance, and (2) specific seismic intervention development.

Study of Building Parameters in Relation to Performance

In this first category are test programs such as Bariola and Sozen (1990), investigating the influence of ground motion, slenderness ratio, and wall thickness on the out-of-plane overturning behavior of adobe walls, as well as Gulkan and Gurdil (1989), an experimental study of the behavior of $1 \times 1 \times 0.3$ m square adobe wall panels subjected to a constant in-plane compression normal to the horizontal mortar joints, as well as to an incrementally applied diagonal load for compressive and shear forces—creating conditions similar to stresses in an earthquake. This investigation, based on a PhD dissertation, determined that failure of the wall panels under the combined compressive load and diagonal loads occurred as joint separation for small compressive loads and as crushing or splitting for large compressive loads.

Vargas Neumann (1993) presented a very compelling paper on *tapial,* or rammed earth, construction in South America and the testing program carried out at the Catholic University of Peru, which addresses both the study of building parameters in relation to performance and specific seismic intervention development. This research focused on the resistance of rammed earth buildings to earthquakes. Seismic resistance of walls was obtained from static diagonal compression tests on $0.60 \times 0.60 \times 0.15$ m specimens and from shear tests on $2 \times 2 \times 0.20$ m walls.

The following parameters were chosen for study because of their supposed significant influence on rammed earth construction:

soil granulometry
water content prior to compaction
level of compaction
use of additives
joint treatment

Eighty-seven diagonal compression test specimens were tested in the process of studying these influences, with the following results. Compression tests on 10 cm cubes, corroborated by diagonal compression tests, indicate a decrease in dry compressive strength, as well as in shear strength, with the increase of sand content in the soil. It was found that, for increasing amounts of water in the mix prior to compaction, the diagonal compressive strength increased, although for practical purposes related to ease of compaction and form stripping, a limit is about 17%.

Compaction increases density and strength to a certain point, after which there is no increase. However, it was found that incorporating the maximum permissible water content prior to compaction had more effect on the shear strength than did the amount of compaction.

Coarse sand added to the clay soils reduces the diagonal compressive strength, but it also reduces the cracking in the walls. However, the water content in these sandy soils cannot be high because of distortion of the wall upon removal of the forms. Straw also reduces the cracking, allowing greater water content without negative effects. Thus, although shear strength was not influenced by simply adding straw up to about 0.5% by weight, the addition of straw allows a higher water content prior to compaction, which in turn results in a greater shear strength.

Joints of stones, gravel, and straw were tested against the natural one of no added material. The diagonal compression tests showed that the best joint is the natural one, roughened and wetted.

By testing the larger wall specimens, it was found that drying cracks in walls do not influence the shear resistance, and they can therefore be treated as cosmetic in nature and can be covered in the wall finishing process. The larger wall specimens were also employed to test the use of cane to reinforce the walls both vertically and horizontally. The cane mesh was tied together with nylon thread. Although the wall specimens without cane reinforcing and with natural joints only were about 100% stronger than those with the cane reinforcing, the cane-reinforced walls avoided the brittle collapse of the unreinforced walls. This fact is more important than the loss of strength due to the introduction of the cane in the horizontal joints.

Specific Seismic Intervention Development

Two seminal research and testing programs in the late 1970s and early 1980s took place at the Institute of Engineering at the National University of Mexico and at the Catholic University of Peru. These research programs developed a great deal of understanding regarding the behavior of earthen buildings during earthquakes, as well as the means of mitigating the severe consequences of the damage to these structures.

The paper presented by Meli, Hernandez, and Padilla (1981) at the International Workshop on Earthen Buildings in Seismic Areas describes the work that was done in Mexico on this topic. Three strengthening methods for five 1:2.5 scale adobe models were tested on a shake table using ground motions from three major actual earthquakes. The three strengthening methods were: (1) a reinforced concrete bond beam at the top of the walls; (2) welded wire mesh nailed to both faces of the walls and covered by mortar, and (3) steel rods tied to both faces in the upper part of the walls. The objective of the reinforcement was to decrease the likelihood of wall separation at the corners and subsequent overturning. All three strengthening methods were found to be effective, with the welded wire mesh being the most efficient. Although these tests and the results were specifically for adobe structures, most of the results are valid for other types of masonry construction.

The most widely used strengthening method for improving adobe seismic behavior is the bond beam in the upper perimeter of the wall. This bonding element can be a wood beam or a concrete beam. Because of its volume changes due to shrinkage, adobe tends to separate from concrete and lose the tightening effect of the bond beam. A ribbed beam, with spurs in the corners, was proposed in Mexico to strengthen adobe houses damaged by earthquakes.

A simpler procedure is the placement of horizontal steel rods at the top of the walls which are slightly tightened in order to precompress the wall. The main advantage of this procedure is that the roof does not need to be removed. A more comprehensive system of reinforcement consists of covering both faces of the walls with a welded wire mesh and a thick rendering of mortar or plaster. Additional bars in the perimeter of the openings and in the upper end of the walls give additional strength.

Material properties of the adobe included a mean compressive strength of 10 kg/cm^2 and 3 kg/cm^2 for the tension test, with a coefficient of variation of 30%. Average properties for wall specimens tested in the laboratory included a shear strength by diagonal compression of 1.3 kg/cm^2, a modulus of elasticity of 2500 kg/cm^2, and a shear modulus of 700 kg/cm^2. The modulus of elasticity and shear strength were increased when cement mortar was used, whereas strength and stiffness were reduced when lime mortars were used. Two full-scale walls were tested under alternating lateral loads, with an average shear strength at failure of 1.1 kg/cm^2.

Due to the limitations of the shake table, reduced scale models were used. To obtain stresses closer to those required for similitude, additional weights were distributed to the walls so that the density of the walls was increased by a factor of the square root of the scale factor, 2.5. The allowable displacement of the shake table was 2.5 cm. Models for the shake table reproduced the typical house structure. Models were placed on the table in such a way that the table movement was perpendicular to the longitudinal walls.

Five models were tested: three were built independently, two of them without reinforcement and one with a concrete bond beam; the two remaining models were actually the two unreinforced models, which were strengthened after they were tested very near collapse.

The amount of damage suffered by the models can be related to their loss of stiffness and the consequent increase in the fundamental period and increased damping. A basis for comparison of results of the different models was an increase of the fundamental period by 50%. This increase was considered to correspond to major damage in the structure.

The first unreinforced model withstood 90% of the El Centro, California, earthquake record but was severely distressed. This model was then repaired and reinforced by filling the major cracks and covering the walls with a wire mesh nailed to the adobe walls and a cement rendering. The repaired and strengthened model then withstood the full intensity of the El Centro, California, and Managua, Nicaragua, earthquake records, as well as 4.6 times the Oaxaca, Mexico, earthquake record. The next model was initially reinforced with a concrete bond beam and withstood 90% of the El Centro record without apparent damage. It was subjected to the full intensity of the El Centro and Managua records without major damage, but it showed major distress as the result of 3.6 times the Oaxaca record. The second unreinforced model was much like the first, but it was subjected to the Oaxaca record only. This model was considered failed at 1.35 times the Oaxaca record. It was then reinforced with steel tie-rods at the tops of the walls. It then withstood twice the intensity that caused the unreinforced model to fail.

Use of wire mesh is considered the most efficient method of reinforcing existing adobes. Not only does it enhance the seismic safety, it also protects the adobe from weather. From the viewpoint of cost and ease of construction, the intervention of the steel ties at the top of the walls is most convenient. However, it was felt that additional vertical ties at the corners would achieve a higher degree of safety. Several additional details should be considered in order to obtain proper safety: roof diaphragm, connection of roof and walls, and reinforcement around openings.

At the Catholic University of Peru (PUCP) in Lima, Vargas Neumann and colleagues (Vargas Neumann et al. 1984) first studied the factors that influence the strength of adobe masonry, including (1) material properties of the soil used; (2) drying process (issues of shrinkage cracking); (3) effect of additives such as lime, cement, and a dispersing agent such as sodium carbonate; and (4) the construction process. Simple field tests devised to identify the most adequate materials for adobe construction and ones easily transmitted to the potential adobe builder were then proposed. Later, shake table tests on eight full-scale models representing one-story rural dwellings were carried out at the Structures Laboratory of PUCP in Lima. Ottazzi and colleagues (Ottazzi et al. 1989) summarize the findings from these shake table tests. Along with control specimens constructed with traditional techniques, various improved construction techniques were tested and compared, including the addition of straw and coarse sand to the mud mortar to reduce cracking, internal horizontal cane mesh, vertical cane reinforcement, and a crowning tie-beam at the tops of the walls. The difference in behavior between unreinforced and reinforced models provided excellent evidence that the internal cane reinforcing combined with the tie-beam at the roof level greatly improved the seismic performance of the adobe structures. Improvement in the quality of materials and workmanship effectively increases the wall strength and stiffness, but it must be complemented by the addition of structural reinforcement, in order to prevent collapse.

Other related testing programs followed at the Structures Laboratory of PUCP, including a retrofit study following the 1983 Popayan earthquake in Columbia (Torrealva 1987). Some of the adobe houses damaged in the Popayan earthquake were repaired and strengthened with a wire mesh at the corners and covered with a cement plaster—the purpose being to prevent separation of the walls at the corners. A shake table test program was carried out at PUCP on two full-scale adobe specimens to determine the efficiency of this repair and seismic intervention scheme. The first module was tested first without the intervention; next it was repaired and strengthened with the wire mesh and cement plaster system and then tested again. The second module was first strengthened and then tested. While significantly increasing the seismic resistance, these interventions resulted in new patterns of failure that may be avoided by introducing additional features in the intervention scheme.

The wire mesh is attached to both sides of the wall with nails or wire through the wall thickness. The wire mesh extends from the bottom of the foundation up over the wooden ring beam at the top of the wall. The nails are spaced at 30 cm. The mesh is covered with a concrete plaster up to 4 cm in thickness.

Conclusions of the testing program include:

- wire mesh applied to the surface of the walls prevents out-of-plane failure; when covered with cement plaster, it also increases the resistance to shear forces and overturning;
- four-inch nails at 30 cm on center were enough to hold the mesh in place during the shaking;
- partial out-of-plane failure can be avoided by the addition of a horizontal strip of mesh at the top of the wall;
- the greater the surface area covered by the mesh, the greater the seismic resistance.

In addition to testing programs on adobe in North and South America in the 1970s, ’80s, and ’90s (the latter dates corresponding to the tests conducted in the United States at the University of California, Berkeley, and at Stanford University, not addressed in this review), relevant tests were conducted in Europe on stone and brick masonry at the Institute for Testing and Research in Materials and Structures in Ljubljana, Slovenia, the former Yugoslavia. Tomazevic, Velechovsky, and Weiss (1992) conducted tests on three two-story stone masonry buildings. Tomazevic, Lutman, and Weiss (1996) conducted shake table tests of the efficacy of adding steel wall ties and/or replacing wooden floors with reinforced concrete slabs in existing brick masonry buildings. They found that rigid slabs and steel ties significantly improved the seismic behavior of these buildings. Wooden floors may be replaced by reinforced concrete slabs and anchored to supporting walls, or the walls can be tied with steel ties and the wooden floors anchored to the walls and/or braced with diagonal ties. Based on the test results, a simple method for designing the ties was proposed.

Tomazevic and Zarnic (1985) tested the effect of horizontal reinforcement and mortar strength on the strength and ductility of sixteen small-scale masonry wall specimens, 400 x 607 x 63 mm, subjecting them to cyclic lateral loading. At shear failure, the horizontal reinforcement significantly improved the ductility of the walls, but it had no effect on lateral resistance. Large amounts of reinforcement were not found to be effective because of inadequate bonding and anchorage conditions at shear failure.

Sixteen specimens with varying degrees of mortar strength and amounts of horizontal reinforcement were tested under constant compressive load and lateral load reversals. The upper and lower support planes remained parallel during the tests. Reaction forces and bending moments transferred into the upper support beam were measured, as were horizontal and vertical displacement, strain in the diagonal directions, and strain in the reinforcement. During the tests, the crack propagation was also observed and recorded.

Test results included the load-deformation relationship for the walls with and without reinforcement. Shear failure was observed in all tests. First horizontal tension cracks occurred in the joints between the support beams and the wall panels. Then the diagonal cracks developed at the mid-portion. In the case of unreinforced walls, a single diagonal crack developed until instantaneous failure occurred. When failing in shear, the concrete block masonry behaves in a brittle manner with minimum ductility. In the case of the reinforced specimens, many diagonal cracks developed. In some cases the hooks of the reinforcing bars started to straighten. At failure, parts of the wall, already separated by the diagonal cracks, fell out of the wall, or the wall settled down because of the damage to the masonry from splitting and crushing.

It was found that the ductility of the wall could be improved by adding a sufficient amount of horizontal reinforcement. However, after a certain point, the effectiveness of the reinforcement is inversely proportional to the reinforcement ratio. That certain point is the amount of reinforcement corresponding to the lateral resistance of the unreinforced wall. The effectiveness of the reinforcement strongly depends on the bond and anchorage condition, which in this case depended on the mortar strength.

The European Commission sponsored several research and testing programs—some as recently as the 1990s—on stone and brick masonry; these studies are also relevant to earthen architecture. Benedetti, Carydis, and Pezzoli (1998) tested a total of fourteen half-scale model two-story brick and stone masonry buildings, some of which were repaired and strengthened by various interventions and tested again in a total of 119 shake table tests sponsored by the European Commission. These tests were carried out at the Istituto Sperimentale Modelli e Strutture (ISMES) in Bergamo, Italy, and the Laboratory for Earthquake Engineering (LEE) in Athens. The efficiency of various retrofitting methods was studied by using three components of base excitation for each and recording the degradation of dynamic response at the increase of damage. The repair and retrofit techniques used included local sealing of cracks with cement mixture, Emaco, or gypsum; steel mesh nailed to the floor slabs, bent and connected to the walls, and covered with a concrete layer to form a bond beam at the floor and roof levels; and horizontal steel tie-rods applied at each story level and anchored with steel or wood plates at the corners. Simple methods were found to be quite efficient.

Although these tests were done on brick and stone masonry rather than on adobe or other earthen material, the methods of testing would be applicable to further study of earthen materials, and some of the findings and results appear to be quite applicable to earthen construction:

- Repairs and strengthening carried out on damaged buildings stiffened the buildings, such that much of the original frequencies of vibration were recovered.
- Original damping in the structures was only recovered when local sealing of major cracks was used in repair, and used in conjunction with other interventions.
- Ultimate base shear coefficients for brick models were in the range of 0.22 to 0.30, with a common value of 0.30 achieved after repairs and strengthening.
- Ultimate base shear coefficients for stone models ranged from 0.11 to 0.19.
- Structural response modification factor, q, estimated for brick masonry buildings ranged from 1.5 to 1.8 in their original configurations, and it was 15%–60% higher when the buildings were repaired and strengthened.
- Structural response modification factor, q, estimated for stone masonry buildings was approximately 2.0, but these buildings were already stiffened in the original state.

This research concluded that significant increases in lateral resistance might be obtained by simple techniques such as the local sealing of cracks and the application of horizontal tie-rods. The original quality of construction plays a significant role in the benefits that might be achieved by strengthening. Horizontal ties such as tie-rods or reinforced concrete bond beams are very efficient in preventing collapse due to the separation of walls.

Another European Commission–funded project, Innovative Stability Techniques for the European Cultural Heritage (ISTECH), focused on the development of innovative seismic mitigation techniques for restoring cultural heritage structures, primarily masonry buildings, damaged by earthquakes (Castellano et al. 1999). One of the most promising innovative techniques developed was a connection element based on the idea of using a superelasticity material. The use of devices based on superelastic shape memory alloys was shown to be effective in improving the resistance of masonry structures to earthquake shaking. These devices, known as shape memory alloy devices (SMADs) can be used to prestress masonry yet prevent overstressing, because of the Ni-Ti alloy's superelastic force limitation, or plateau. Other types of SMADs are used in situations where no prestress is applied to the masonry; they only become activated during dynamic loading.

The basic idea is to connect the external walls to the floors, roof, or perpendicular walls with these SMADs, such that under low-intensity action, the devices remain as stiff as traditional steel connections do. Yet under higher intensity, the stiffness of the devices decreases, reducing amplification of accelerations and allowing controlled displacements and damage, thereby preventing collapse. Under extreme intensity action, the stiffness of the devices again increases, preventing instability. In addition to these features, the interventions using these devices are reversible, and the resistance of the Ni-Ti alloy to corrosion is greater than that of stainless steel.

Optimization of the SMADs' design parameters was shown to be affected by the mechanical characteristics of the masonry, particularly tensile strength. The main result of this optimization analysis was the insight that a SMAD that is not sensitive to the masonry properties would be useful in real applications where such properties are not known. FIP Industriale in Italy has developed a SMAD with multiple plateaus, or regions where the stiffness decreases. Shake table tests of the FIP device were performed in Italy using three-wythe-thick masonry wall panels 4 m high, with the devices anchored at the 3.4 m height. The results of this test were that the wall with the SMADs did not show visible damage, even when subjected to a peak ground acceleration (PGA) of 50% higher than that which caused collapse of a wall panel that included traditional steel ties. In addition, the acceleration of the top of the SMAD-supported wall was only 50% of that measured for the traditionally strengthened wall.

Large-scale tests on brick masonry walls retrofitted with diagonal SMADs on wall piers were also conducted using a pseudodynamic procedure. In this case, the SMADs were post-tensioned. The effect was a dissipation of about 30% of the total energy by the devices, showing their effectiveness in resisting earthquake loads.

The first applications of these devices are the bell tower of the San Giorgio in Trignano Church in San Martino in Rio, Italy, which was damaged by the 1996 Reggio Emilia earthquake, and the transept tympana of the Basilica of St. Francis in Assisi, Italy, which was damaged in the September 1997 earthquake. The bell tower was retrofitted with four vertical prestressing steel bars in the internal corners of the tower, with a SMAD inserted in series with each rod. The SMADs were made up of sixty Ni-Ti superelastic wires of 1 mm diameter and 3 m in length. The basilica is retrofitted with multiplateau self-balancing SMADs, which connect the transept tympana to the roof diaphragm. Forty-seven devices have been installed, with a maximum displacement of from 8 to 25 mm.

Analysis

Damage/Collapse Patterns of URM Structures

Analytical tools have been used throughout most research and testing programs on earthen building models and components. They have been used to verify test results and to predict seismic behavior. Finite element analysis has generally been the approach for the analysis of specific conditions. However, using these analytical models to predict or illustrate damage and collapse patterns requires more elaborate, nonlinear solutions. Among some of the more innovative developments are two analytical methods developed for determining the collapse patterns of stone masonry structures, principally historic church structures (Casolo et al. 2000; Azevedo, Sincraian, and Lemos 2000). Casolo and colleagues (Casolo et al. 2000) developed simplified material models and numerical analysis to predict and evaluate out-of-plane seismic behavior of old masonry church facades under conditions of varying geometries, material strengths, postelastic material behavior, and excitation characteristics. Comparisons with observed damage patterns of Italian masonry churches damaged in earthquakes of the late 1970s and early 1980s confirm the accuracy and appropriateness of using these numerical models. The method addresses damage typologies for a specific subset of monumental structures—namely, old stone masonry churches—and only the out-of-plane behavior of the facades.

Damage typology study is an integral part of seismic vulnerability evaluations, where vulnerability is assessed by field survey. The objective of an analytical vulnerability approach is to identify expected behavior from field surveys. The expected behavior is based on known reference cases. The numerical model developed in this study is an attempt to provide reference cases.

While the paper focuses on the specific collapse mechanisms that are recurring in well-defined parts of the structure, it is similar to the damage typology approach of the Getty Seismic Adobe Project (GSAP) Northridge earthquake study, which identified recurring damage patterns in historic adobes. However, the numerical aspect allows the assignment of levels of shaking intensity to the damage, whereas the GSAP was only able to assign levels of shaking intensity to overall damage states, not to specific damage typologies.

Well-defined damage and collapse patterns in old masonry churches generally do not involve structural behavior as a whole. Thus, substructuring into macroelements for analysis is used to evaluate the overall behavior of the structure.

Numerical analysis of macroelement behavior is based on geometry and material properties. Correlating numerical analysis with actual observation provides insight into the particular damage and highlights the most significant aspects. The specific material model developed for this study is simpler than most refined numerical models for masonry, but it is still capable of modeling behavior in the nonlinear range.

In many cases, seismic action on the facades appeared to divide them into rigid blocks connected by highly degraded zones, following simple and recurrent fracture patterns. The masonry was primarily two wythes of partially cut stone, with full cut stone used at the corners. Brickwork was absent.

Activation of specific damage typologies to specific facade geometries depended primarily on the material properties and excitation characteristics. The strength of the masonry as well as the postelastic material behavior affect the damage patterns, as do the actual ground shaking characteristics. Differences in accelerograms reflect both the level and the type of damage. The correlation between damage level and PGA, however, is not strong, indicating the need to use more than a single earthquake-related parameter.

As another part of the European Commission–funded project (ISTECH), Azevedo, Sincraian, and Lemos (2000) utilized a discrete element method (DEM) analysis technique, which falls within the general classification of discontinuous analysis techniques, to analyze the seismic behavior of masonry structural systems, particularly stone masonry structures. The DEM represents a structure as an assembly of component blocks in mechanical interaction across joint surfaces. It is shown that the method is capable of reproducing the important phenomena of crack opening and joint sliding. It has the ability to simulate progressive failure associated with crack propagation and large displacements/rotations between blocks. It is also capable of including reinforcing schemes, such as vertical and horizontal cables that link two different blocks. The blocks can be adjacent to each other or far away from each other. In some situations, cables are placed in holes drilled through the blocks, such as in the case of center cores drilled vertically in a wall. Thus there is a contact between the cable and the blocks, not only at the attaching points but also in the blocks that are crossed by the cables. Because of the lack of reversibility, this application is being increasingly disregarded in favor of reinforcing with cables or bars only on the exterior.

One of the goals of this research was to assess the collapse patterns of different structural elements when subjected to self weight and seismic action, starting with simple arches and columns and progressing to more complex structures, such as a bell tower and an aqueduct. Because the analysis method also allows for the inclusion of tension-reinforcing elements, different retrofit schemes can be studied and mitigating effects compared. These seismic vulnerability (or fragility) functions compare some control parameter, such as maximum displacement, to the seismic intensity parameter, such as the PGA.

Specific Seismic Intervention Development and Prediction of Performance

This analytical tool can be used to evaluate specific seismic interventions into these structures, such as the introduction of vertical and horizontal tie-rods or cables in the bell tower of the San Giorgio church. Other analytical methods have been used to evaluate the potential for base-isolating masonry structures. Qamaruddin, Al-Oraimi, and Al-Jabri (1996) review worldwide developments of the friction seismic isolation (FSI) scheme for masonry buildings, in which the isolation mechanism is purely sliding friction. The results of the analysis show that the seismic response was significantly limited by the use of graphite powder or screened gravel as sliding materials at the base of the multistory brick building. Suitable coefficients of friction for masonry structures were found to range from 0.10 to 0.20.

Sincraian and Guerreiro (1996) demonstrate that the behavior of base-isolated, brick masonry structures can be represented by a bilinear model. Columns and arches made of stone are modeled by a fiber element representing the cross section of stones and having limited resistance in tension. A nonlinear infill panel element is used to simulate the brick walls. The results show that this type of structural system, especially if it has a large mass, can benefit greatly from base isolation. Internal forces as well as deformations would be greatly reduced.

Conclusion

Research related to the seismic deterioration/pathology of earthen architecture include—but are not limited to—base isolation repair of earthen walls and its influence on seismic performance; analytical techniques leading to the prediction of seismic damage patterns; and determination of and understanding earthen building damage typologies based on damage surveys, laboratory tests, and predictive analytical models. The process of recognizing the types of seismic damage and relating them to causes and ground shaking intensity (vulnerability analysis) is an important tool in developing effective means of mitigating these damages in future seismic events. Some of this research has been conducted and reported in the literature, and some of it is directly related to earthen buildings, but more information is available regarding other types of masonry, such as stone and brick. Although these materials differ from earthen materials in many respects, seismic performance is often quite similar. Therefore, the research and testing of buildings built of these materials are often relevant to the seismic deterioration/pathology of earthen architecture.

Research related to developing, executing, and evaluating seismic interventions in earthen architecture includes, but is not limited to: simple stability-based interventions, such as wall center cores, partial roof diaphragms, strapping and through-wall ties (some of the topics pursued during the GSAP program); the reintroduction or continued use of traditional building methods in local seismic cultures to reduce the seismic vulnerability of buildings (as suggested by the European University Centre for Cultural Heritage in Italy, and as observed by Erdik and Gulkan 1993); and research related to base isolation and shape memory alloy devices (SMADs) used to improve the stability response of cultural heritage structures. The research efforts related to earthen architecture are many, and they may be extensively enhanced by looking to the several and varied research and testing efforts on stone and brick masonry interventions, most of which are applicable to earthen architecture as well.

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Conservation of Earthen Archaeological Sites

By Anne Oliver

Of the many types of earthen architectural heritage, archaeological sites are particularly vulnerable to deterioration. Inhabited earthen structures are made habitable by the existence of foundations and roofs, functioning drainage systems, and the maintenance or reapplication of protective renders. Archaeological sites are, by definition, uninhabited: roofs may be missing or only partially in place, foundations and drainage systems may be destroyed, walls may no longer be standing, and much of the original structure may be buried. To complicate the issue, repair and maintenance strategies applied to inhabited earthen structures are often deemed inappropriate for archaeological sites. In many modern cultures, the value of the archaeological site is derived from the physical remnants of a lost culture or tradition, rather than from the cultural traditions by which it was constructed and maintained. Cyclical maintenance and renewal of roofs, foundations, and surface finishes using traditional methods and materials are often not acceptable or even practicable, given the commitment of human and material resources necessary to conduct them.

Archaeological sites can be divided into three broad groups, which are often found in combination at a single location: unexcavated, above ground, and excavated. At unexcavated earthen sites, the architecture may be a constructed or natural mound formed by the accumulation of soil over the structure, or it may be buried below grade. These sites have generally reached equilibrium and stasis, although the balance may be upset by any change in the environment or simply by the ongoing processes of deterioration, particularly in the case of constructed mounds.

In contrast, above-ground ruins and excavated sites are much more vulnerable to deterioration. They are subject to the long-term impacts of temperature, wind, and moisture (in the form of humidity, precipitation, and groundwater) and to the less foreseeable but often more catastrophic impacts of vibration and seismic activity, vandalism, lightning or extreme weather, animal activity, plant growth, and so forth. Especially vulnerable are sites under excavation. As work proceeds, the earthen materials move from the stable buried environment, with relatively constant temperature and moisture, to the unstable environment of the open air. The transition from burial to exposure can wreak major destruction in a very short time if the transition is not carefully controlled. Rapid drying of earthen materials is particularly problematic, as the component clays shrink, the earthen materials crack, and the weak chemical and mechanical bonds are broken. As well, many sites are only partially excavated, and the differences in fill levels, particularly in subterranean spaces, can create problems as moisture migrates through the fill and then through the architectural elements to the evaporative front. In these situations, where the architecture is literally a part of the land, it is often possible only to address the symptoms of deterioration and not the causes.

Each earthen archaeological site presents a unique set of challenges in terms of the complexity of deterioration factors that impact the architecture, the philosophy of conservation driving decisions, and the physical interventions that may be implemented. Of the many conservation treatment alternatives, there is a core of physical interventions that are particularly relevant to earthen archaeological sites. These include preventive measures during excavation, wall caps, temporary and permanent shelters, reassembly and reconstruction, burial and site stabilization, and removal and relocation. Other common interventions, such as structural and seismic stabilization; drainage modification; biological control; the conservation of decorated and undecorated surface finishes; and the use of consolidants, water repellents, and modified earthen materials for repair are discussed elsewhere in this literature review. Following is an overview of the published research relating to the development, execution, and evaluation of these interventions, as well as suggestions for future research to complement, supplement, or redirect these efforts.

Overview of the Published Literature

In general, the published literature pertinent to archaeological site conservation is contained in conference preprints and proceedings, most importantly in the publications that arose from the series of international conferences on earthen architecture held in Lima, Peru, in 1983 (ICCROM, Regional Project on Cultural Heritage and Development UNDP/UNESCO, and National Institute of Culture [Peru] 1985); Rome in 1987 (Rockwell et al. 1988); Las Cruces, New Mexico, USA, in 1990 (Grimstad 1990); Silves, Portugal, in 1993 (Alçada 1993); and Torquay, England, in 2000 (English Heritage, ICOMOS-UK, and University of Plymouth Centre for Earthen Architecture 2000). Several other conference publications are more specific to archaeological sites, although the majority of the contributions pertain to the conservation of objects rather then architecture; these publications include *In Situ Archaeological Conservation* (Hodges and Corzo 1987) and *Conservation on Archaeological Excavations: With Particular Reference to the Mediterranean Area* (Stanley-Price 1984; 1995). Additional relevant papers were written for more broadly based preservation conferences and also for those in allied fields, particularly soil science and geotechnical engineering.

Though informative, conference preprints have inherent drawbacks. Most often only the abstracts of papers are submitted to the selection committee, and the subsequent papers are generally not subject to peer review. And in this format, probably because of the limitations of space, it seems difficult to balance the general and the specific to arrive at a quantity and quality of information that is useful to others. Many papers discuss the general approach and problems at a site, often giving insufficient detail, or they address a particular intervention in a paper that is usually more detailed and useful but that often presents a myopic view of the site.

General overviews of the field, ranging from brief articles to monographs, provide historical perspective and summarize the established norms for conservation interventions at earthen archaeological sites (Alva Balderrama and Chiari 1995; Matero 2000; Richert and Vivian 1974; Stevens 1982 and 1984; Stubbs 1995; Taylor 2000; U.S. National Park Service, Preservation Assistance Division, Technical Preservation Services 1978; Torraca 1976; Viñuales 1981). A number of more general books also contain information specific to the preservation of adobe and/or archaeological sites (Ashurst and Ashurst 1988; Skibinski 1991; Stanley-Price 1995; Torraca 1981; Warren 1999). The types of conservation interventions deemed appropriate or inappropriate today are generally consistent, although the preference of the author for a certain type of treatment (shelter, reconstruction, consolidation) is often evident.

Books on modern earthen construction can sometimes be useful in documenting and preserving traditional technologies and in describing materials, traditional and otherwise, for repair and conservation. Site-specific reports, which are difficult to access, or in-depth case studies, which are relatively rare, can provide a good overview of the preservation philosophy and conservation techniques employed, and they sometimes include an evaluation of their effectiveness (CRATerre and Ecole d'architecture de Grenoble 1989; Plenderleith, de Beaufort, Voûte, and ICCROM 1964; Plenderleith, Voûte, and de Beaufort 1964; Chiari and UNESCO 1975). Publications related to training workshops in earthen architecture and earthen archaeological site conservation can also be useful, although these are by default usually quite site specific (ICCROM, Regional Project on Cultural Heritage and Development UNDP/UNESCO, and National Institute of Culture [Peru] 1985; Mathewson 1989).

The journal *Conservation and Management of Archaeological Sites,* begun in 1995 and subject to rigorous editing, has and should continue to provide a reliable and accessible forum for the dissemination and discussion of conservation interventions for archaeological sites, as should other preservation-oriented journals. Scientific journals and books from related fields, particularly soil science, hydrology, and geotechnical engineering, may also contain relevant information or articles (Armbrust and Dickerson 1971; Armbrust and Lyles 1975; Broms 1988).

Other important resources are bibliographies that focus on earthen architecture (George 1973; Barnes 1975; ICCROM 1981; Getty Conservation Institute 2002; Odul 1993) and an annotated bibliography on the management and conservation of archaeological sites (Demas 1999). Also of potential utility is the Gaia Project Research Index (Dassler et al. 1993), a database of current research projects in the field of earthen architecture that is maintained at ICCROM.

Policy, Planning, and Management

The complexities of earthen archaeological site conservation demand a high level of preservation planning, policy formation, and site management, whether for sites under active excavation or for sites where excavation has long ceased. Fortunately, the literature on cultural resource management and archaeological site management is extensive and very useful (Demas 1999). But there is little written regarding the development of preservation policies or plans for earthen archaeological sites in particular, whether prescriptive or as developed for specific sites (the few exceptions are Chadburn and Batchelor 2000; Galdieri 1981; Gamboa Carrera 1993; Sodini 1984; Van Balen 1990; and Warren 1999). At sites under active excavation, the imperative nature of collaborations among archaeologists and conservators, engineers, and other preservation professionals has only recently been recognized and promoted (Albini, Cobau, and Zizola 1996; Chiari 1985; Leconte 1996; Roby 1995; Sodini 1984), and in fact, such collaborations may be more regularly practiced than is reflected in the literature. Whatever the case, it would be extremely valuable to conduct international research on the development and implementation of preservation planning, policy formation, and site management for earthen archaeological sites before, during, and long after excavation. The information should be synthesized and used to develop, at the least, a set of guidelines outlining recommended procedures and, at best, a handbook that would assist the planning and decision-making process of all those involved in the preservation and presentation of earthen sites.

No Intervention

It is not a glamorous or often-reported choice, but the decision not to intervene at an earthen archaeological site is an important one. The decision may be influenced by philosophy (especially the objections of associated cultures), an evaluation of the site that indicates that it is stable (Emerson and Woods 1990), or, most commonly, lack of funds. But what are the impacts of no intervention? A substantiated account of what happens to a site after the decision not to intervene provides a powerful argument for intervening, or not, in the future. The impacts of no intervention are best evaluated by monitoring deterioration and associated environmental parameters; this can be accomplished through techniques ranging from simple recorded observations, to regular photography, to the installation of monitoring instrumentation. The methods for monitoring deterioration are well understood and transferable from related fields, but a summary of the most useful and effective methods for earthen archaeological sites would be a valuable contribution to the literature. In addition, a broad-based study of monitored but untreated sites could provide valuable information on processes of deterioration and on the viability of no treatment as a preservation option under a variety of circumstances.

Preventive Measures during Excavation

Most of the literature on preventive measures taken for the conservation of architectural materials during excavation pertains to stone, brick, or mosaics. These materials are relatively stable compared to earth, and interventions are largely confined to the installation of temporary shelters or backfill during or between excavation seasons (Alva Balderrama and Chiari 1984 and 1987; Carroll 1998; ICCROM and Rijksuniversiteit te Gent Faculty of Greek Archaeology 1986; Stanley-Price 1984; Roby 1995). Several early articles propose dewatering sites to permit excavation by installing wells, pumping groundwater, and thus lowering the water table temporarily (Ehrenhard 1979; Plenderleith, Voûte, and de Beaufort 1964). The implications of this intervention both during and after excavation are numerous, although the technique may be too expensive, radical, and unpredictable for common use.

But very little is written on preventive measures for earthen architecture, which is much more vulnerable to the rapid environmental changes brought about during excavation. The small body of literature focuses on decorated surface finishes (Chiari et al. 2000; French 1987; Rainer 1995; Xu 1988), but more research has been done than is reflected here. The push must be to publish this information and begin a dialogue, share ideas, and look for new alternatives. Further research is warranted into the use of temporary vapor barriers or insulators (polyethylene sheeting, styrene chips or styrofoam beads, perlite, clays, etc.), other means of controlling the rate of drying, methods of desalination, the installation of shoring against fragile walls or finishes, and the stabilization and removal of architectural elements from the site.

Wall Caps

The unprotected tops of walls at excavated sites or standing ruins are commonly protected with caps. The composition and appearance of caps can vary widely, although there are three predominant types: prefabricated blocks, renders, and small roof-like structures. Prefabricated blocks, or adobes, are installed on flat wall tops that often must be prepared by removing one or more courses of deteriorated original material. The blocks can be composed of unmodified or modified earth; modifiers have included inorganic additives (lime, hydraulic lime, cement, fly ash, brick dust, and other pozzolanic materials), organic additives (bitumen, plant extracts or mucilage, dung, termite saliva, etc.), and synthetic organic polymers (acrylics, polyvinyls, and latex). Renders are similar in composition and are applied directly over the wall tops; again, some removal of deteriorated material may be necessary, but perhaps not as much as required for blocks. Renders are especially useful for walls with very narrow tops, but renders are also more prone to cracking and failure. Small, gabled, or shed-roof-like structures are common on contemporary constructions (corral walls, garden walls, etc.) but are less common on archaeological sites. These may be composed of wood, cane, straw, or more durable materials like stone, slate, or tile. And in a few cases, wall tops are consolidated (e.g., with ethyl silicate or polyurethane) to create a de facto cap or to prepare the original surface for a new cap.

The composition and purpose of the cap vary with the climate. In arid areas with short bursts of precipitation, caps are commonly of soft, permeable materials (earthen or modified earthen blocks or renders) that either shed water away from the wall or distribute water evenly over the vertical wall surfaces. In climates with greater precipitation, less permeable and more durable materials are used (thatch, slate, tile, terra-cotta, stone, brick), which are designed to deposit water well away from the vertical wall surfaces. In all cases, drainage of water away from the wall bases is critical, as is ongoing maintenance of the cap.

A moderate amount of research and discussion on caps has occurred over the past forty years, although there is comparatively little reporting on their long-term performance. Most caps were developed for specific sites and derived by trial and error. Comparative studies of capping alternatives, whether on test walls or original walls, are published only rarely (Chiari 1990a; Hartzler and Oliver 2000; Morales Gamarra 1985; Taylor 1988 and 1990), although much more informal and unpublished research doubtless exists. The simple purpose of the cap is to protect the wall top, and often the vertical faces of the wall, from erosion. But a host of issues make this more difficult than it sounds. The issues that must be addressed include:

- the kind and amount of preparation, or often destruction, of the original wall top that is necessary to prepare a sound surface for the cap
- the material composition and durability of the cap
- differences in physical and mechanical properties between the cap and the wall (especially water and vapor permeability and coefficients of expansion and contraction)
- the intensity and direction of surface water flow from the cap
- drainage at the wall base
- the aesthetic impact of the cap on the wall and the site

A good review of capping materials and techniques from the 1960s through the 1980s was conducted by Taylor (1987), with particular reference to unpublished papers presented at the 1972 Yazd conference, Premier Colloque International sur la Conservation des Monuments en Brique Crue, and oral interviews with authorities in the field. Throughout the literature, the use of adobe modified with cement, lime, or bitumen was most common, sometimes with low proportions of modifier (Torraca, Chiari, and Guillini 1972; Alva Balderrama and Chiari 1984 and 1987), but often with rather high proportions (1:4 or 1:5) (Taylor 1987; 1988; 1990). The use of blocks modified with polyurethane (Pencapsula) was also very common in the United States in the 1960s and 1970s. And unmodified earthen plasters or adobes continued in use; straw chopped short was common in both modified and unmodified caps. Other traditional capping techniques were also advocated, including the use of overhanging layers of brush topped with earth; gypsum; small gabled roofs of wood, cane, and straw; and canted and overhanging caps of ceramic tile or flagstone.

A recommendation frequently repeated throughout the years has been the continued use of traditional capping techniques until further research could provide better alternatives. And by the 1980s, many modified caps had been removed and replaced with unmodified caps because of what was perceived as accelerated erosion of the original wall beneath the cap (Caperton 1988 and 1990; Hartzler and Oliver 2000). The trend was further toward unmodified earthen caps and other traditional modifying materials (particularly cactus mucilage), as well as the traditional techniques described above (Hoyle 1990; Taylor 1987). But unmodified and traditionally modified caps are relatively fugitive and require frequent maintenance, and this in turn proved impractical at many sites where such a commitment of time and resources could not be guaranteed (Alva Balderrama and Chiari 1984; 1987).

Thus, in the 1990s, earthen caps containing low proportions of modifiers (10%) were commonly used (particularly cement, hydraulic lime, and acrylics, although there was some experimentation with lime, hydraulic lime, and polyurethane), in order to increase durability without greatly affecting the permeability or mechanical properties of the adobe or render (Bendakir and Vitoux 1993; Chiari 1990a and 1990b; Gallieri 1993; Hartzler and Oliver 2000). An unusual experiment involved the construction of an unmodified earthen crest on irregular wall tops, followed by the spray application of an acrylic-modified render and a water repellent (Selwitz 1995). Another involved a two-part system for which an outer ring of earth modified with 12% cement and chopped straw was constructed on the wall top and then infilled with earth modified with 6% cement. The permeable infill material absorbed water, prevented runoff over the vertical wall faces, and permitted water vapor transmission through the wall top, while the outer ring held the weaker material in place (Bendakir and Vitoux 1993). Less permeable caps of traditional design, like thatch, continued to be used in wetter climates (Bouwens 2000).

Throughout the literature, empiric observations of the damage caused by caps are rife. The few attempts to evaluate the long-term performance of caps are also based largely on qualitative observations (Chiari 1990a; Taylor 1990). It would be very helpful to separate, in a quantifiable way, the effects of natural erosion on upper wall faces from the effects of any accelerated erosion that may be caused by caps. This might be done by designing an experiment that measured, at frequent time intervals, the rates of erosion in walls capped with materials of varying composition and design versus uncapped controls. Capping materials and methods, as well as potential modifiers for earthen blocks or renders, include all of those discussed above. The effects of different cap designs must also be considered, including the amount of overhang, the degree of incline, the presence or absence of a drip edge, and so forth. The installation of monitoring rods in the caps and walls would provide quantitative data on the location and rate of erosion through time and facilitate comparisons among different types of caps. If the experiment were repeated in several representative environments (arid, temperate, tropical, etc.), the results would allow for a fundamental understanding of the impacts of different caps on the erosional rate of the underlying earthen wall.

After the effects of natural and accelerated erosion are separated, it would be useful to pinpoint the exact processes by which some caps cause accelerated erosion of adobe walls. An intensive study of an unmodified control cap, caps that were proven to cause accelerated erosion, and the underlying adobe walls could be conducted; this study would collect information on temperature, relative humidity, moisture content, soluble salt content, permeability, porosity, and so on, allowing for insight into this phenomenon. From this data, it might be possible to develop general guidelines for design, permeability, and other physical and mechanical properties of an effective cap.

Once the causes of accelerated erosion have been pinpointed, directed research into alternative capping materials and designs could be conducted in order to develop a range of durable caps that protect wall tops but do not cause accelerated erosion or otherwise adversely impact the walls. Capping is rarely installed independently of other interventions, such as consolidation, application of renders on vertical wall faces, and so forth. Thus, not only potential caps but potential systems of intervention should be researched when possible or applicable.

The permutations of capping materials, designs, and intervention systems are endless, and the requirements of a site can be particular. To limit the variables and ensure applicable results, the design of future research projects might be guided by issues of necessity (based on environmental and erosional monitoring), cost, repeatability, ease of installation, frequency and extent of maintenance, and aesthetics. Admittedly, the heterogeneous nature of adobe, even within a site, and the highly variable climatic conditions among sites dictate caution when translating results from one site to another. However, the striking uniformity of capping materials and techniques described in the literature and applied to a wide variety of sites argues that a good cap at one site could be a good cap at many other sites.

Temporary and Permanent Shelters

Shelters are constructed at archaeological sites most often to protect ongoing excavations (and the excavators), mosaics, decorated finishes (often on or of earthen plaster), and earthen architecture. The literature on shelters is rather extensive. While only a portion of it pertains directly to earthen archaeological sites, the issues raised at other sites are pertinent, and many of those publications are also considered here. The issues most germane in the course of shelter design and construction include:

- the physical impact of the shelter on the protected portion of the site (most commonly changes in the level of moisture, whether surface water, groundwater, or humidity; temperature; wind speed and direction);

- the physical impact of the shelter on the unprotected portion of the site and the surrounding landscape (most commonly relating to drainage and the insertion of heavy anchoring systems into cultural deposits);
- the aesthetic impact of the shelter on the site and the landscape;
- the level of visitation and the degree to which the shelter must facilitate interpretation and/or separate visitors from the site;
- the cost of shelter construction;
- the cost and realization of shelter maintenance.

A few site-specific studies were published in the 1960s, but most of the earthen architecture literature dates from the 1980s to the present, spurred by the resolutions of the 1980 Ankara conference (Üstünkök and Madran 1980) for further research into temporary and permanent shelters (see Alva Balderrama and Chiari 1995 for a summary of resolutions). The published literature is pervasively site specific; to some degree it must be, because each site is unique. It is also predominantly concerned with the design and aesthetic aspects of shelters. There are a few good overviews that discuss the problems and potential solutions of shelter design and construction (Gollmann 1987; Schmidt 1988), as well as a very useful annotated bibliography (Demas 1999). As well, the proceedings of a colloquium on shelters, convened in Arizona in 2001, have been published in a special volume of the journal *Conservation and Management of Archaeological Sites* (Stanley-Price 2001).

Minissi (1985) describes the four main types of shelters that have evolved over the years:

1. simple, purely functional and inexpensive shelters, often temporary but usually becoming permanent, which ignore the artistic or architectural values of the archaeological remains;
2. single roofs covering large expanses, but without any formal spatial relationship to the protected remains;
3. shelters, usually over particular areas of artistic value, that meet museographic requirements of protection and viewing but create their own quite arbitrary volumes;
4. shelters, usually over particular areas of artistic value, that go beyond basic museographic needs and relate directly to the spatial arrangements of the ruins.

The trend in shelter design has generally been from the former to the latter, with increasing collaboration among archaeologists, conservators, and architects. However, there also seem to be trends within countries or regions, shaped perhaps by climate, the type of archaeological resource, the extent of material and financial resources, and the degree of acceptance of shelters of one kind or another. For instance, big enclosed halls are popular in Germany, Austria, and Switzerland; more striking design solutions are common in the warmer countries of western Europe and the Middle East. Big halls with museums pervade China, while more ephemeral shelters constructed of traditional materials are used in South America and Africa. In addition, there seems to be a tendency to shy away from shelters in some countries such as the United States, in contrast to the widespread use and acceptance of shelters in other countries such as Israel.

Prior to the selection of a shelter for site protection, some efforts at cost comparison or cost-benefit analysis are presumably conducted, but, with few exceptions (Bikai and Bikai 1997; García-Bárcena 1987), these efforts are reported in the literature tangentially, if at all. The field would benefit from a more rigorous presentation, analysis, and discussion of the relative costs and potential benefits among not only different shelter designs but among a wide range of conservation options (e.g., no treatment, ongoing repairs with caps and protective coatings, shelters, burial, or a combination thereof). Both initial expenditures for design and implementation, as well as ongoing expenditures for monitoring, evaluation, and maintenance, should be considered.

The literature focuses on design and aesthetic issues, but the chief function of a shelter is to protect. Is this being done? There is almost no quantitative, scientific research reported on environmental and condition monitoring—either before shelter construction that would warrant its use, or after shelter construction that would justify its existence or confirm observations that it was either protecting the site or causing increased deterioration. The few evaluations of existing shelters are largely confined to empiric observations, and these observations are largely confined to the deleterious aspects of shelters (e.g., an increase in condensation and humidity or, conversely, dehydration of the earthen materials; the creation of harmful new wind patterns; inadequate drainage systems, etc.) (Bahn, Bednarik, and Steinbring 1995; Barker 1986; de la Torre 1997; Stevens 1986). There is often little question that the shelter has reduced the rate of deterioration, particularly from the direct impact of precipitation, but again this cannot be quantified, because no monitoring was conducted before and after shelter construction (Matero et al. 2000; Mazar 1999).

It would be very useful to develop consensus on a methodology for designing and evaluating physically effective (in addition to aesthetically appropriate and didactically useful) shelters. The methodology might then be used by archaeologists, conservators, architects, engineers, and site managers at a wide range of earthen archaeological sites to evaluate the need for a shelter, select from among several shelter options, design a shelter, evaluate an existing shelter, and/or modify an existing shelter. Such a methodology might include the following tasks:

1. Assess the environmental conditions and deterioration factors affecting the site prior to shelter construction or modification (presumably done prior to the selection of a shelter as the most effective option).
2. Develop shelter designs or modifications based upon the data collected above, in combination with other factors like financial resources, site aesthetics, the didactic or interpretive purpose of the site and shelter, and so forth.
3. Test small model shelters or selected shelter materials over test walls or portions of the site, if possible or useful.
4. Select and construct the site shelter.
5. Monitor environmental parameters inside and outside of the shelter, and monitor the physical condition of sheltered and (if applicable) unsheltered portions of the site.
6. Analyze the data and publish the conclusions and recommendations of the project.

In short, by understanding the environment, we can design an effective shelter, and by evaluating the shelter, we can develop better designs.

Two articles present the results of environmental monitoring as a method of evaluating the impact and effectiveness of shelters (Agnew et al. 1996; Theoulakis 1993). In the more extensive study (Agnew et al. 1996), a shelter was erected over one of two adobe test walls, and environmental parameters in and around both walls were monitored; these included temperature (air, ground, wall surface, and wall interior), relative humidity, wind speed and direction, precipitation, and solar radiation. "Quantitative data for the shelter in the form of 'protective indices' were determined by comparing meteorological parameters inside and outside the shelter, and temperature variability on two identical adobe test walls likewise under and outside the shelter. By restricting the use of data to paired observations on the sheltered and exposed walls it was possible to establish its performance in reducing (or otherwise) environmental variations within the shelter" (Agnew et al. 1996, 139).

This system was fairly elaborate and was applied to two small test walls; thus it may not be easily applied to all sites or situations. However, it can serve as a foundation for the development of procedures for evaluating the environmental conditions affecting a site and evaluating the impact and effectiveness of a proposed or existing shelter. Additional parameters like drainage patterns, ground moisture, and wall moisture might also be monitored.

Comparative research is warranted into different types of shelter designs and shelter materials. If sufficient environmental parameters can be defined, computer modeling of potential shelter designs may hold great promise. Computers aside (or in order to calibrate and test the effectiveness of a computer model), it would be quite interesting to construct a series of test walls, erect a variety of shelters, and monitor the environmental parameters outlined above in order to gain a better understanding of the effects of different designs and materials. Variables might include the type of design (flat roof, shed roof, gable roof, dome, etc.), the degree of enclosure (fully enclosed, partially enclosed, and open sided), types of materials (metal, stone, concrete, geotextiles, glass, plastics, wood, traditional materials), permeability to moisture and air, material color and transparency or opacity, and so forth. Distinctions might also be made between temporary and permanent shelters. As well, the interesting concepts of diurnal and seasonal shelters (Hinkel 1967–68; Maekawa and Agnew 1996) deserve further development and evaluation. As with caps, the variations should be bounded by the particular considerations of the site or region under study, including cost, repeatability, ease of installation, frequency and extent of maintenance, and aesthetics. While admittedly broad in scope, the lessons of comprehensive studies of this sort would be of immense benefit. Comparative studies of existing shelters are warranted as well, to measure their effectiveness in terms of physical protection, cost, interpretive or didactic function, integration with the site or landscape, aesthetics, and popular appeal.

In addition to these recommendations, the resolutions of the Ankara conference of 1980 still pertain (Üstünkök and Madran 1980; Alva Balderrama and Chiari 1995). These include research into low-cost shelter constructions, both temporary and permanent, and the continued development and testing of design concepts by professionals in the related disciplines of archaeology, architecture, and conservation. Publications should focus equally on the process and the result, and preferably from the standpoint of both design and conservation.

Reconstruction

Fragile and eroded earthen archaeological sites do not lend themselves to reassembly, or anastylosis, and the practice is not common. In certain instances, detached sections of a monolithic construction may be mechanically reattached, or a recently collapsed adobe wall may be reassembled. Reconstruction is more common, and may vary in extent from the partial reconstruction necessary to integrate existing elements, buttress walls, direct visitor traffic, or facilitate interpretation (Hartzler and Oliver 2000; Marchand 2000; Orazi 2000) to the proposed or actual full reconstruction of a lost structure (Emrick and Meinhardt 1990; Smith 1986; Stevens 2000). The methodology for reconstruction is well established: in most cases, research is first conducted into the original forms, materials, and methods of construction, which then guide the new construction. Materials may be modified to increase durability, and efforts are made to distinguish repair from original materials. In some cases, original earthen materials may be reconstituted to form reconstructed elements.

But all reconstructions impact an archaeological site physically and aesthetically, and few publications address these impacts at earthen sites. Extensive partial reconstructions or full reconstructions can have effects similar to those of shelters, and the recommendations for further research described for shelters (see above) apply equally to large-scale reconstructions. The field would benefit from critical reviews of the effectiveness of existing reconstructions; such reviews should address issues of design, interpretation, impact on environmental conditions and original materials, monitoring, maintenance, and cost (both total and in relation to other alternatives).

Backfilling, Burial, and Site Stabilization

In the past twenty years, backfilling and burial (or reburial) have been recognized as a potentially effective method of preserving archaeological sites, and the body of literature has grown accordingly. A number of articles and a good annotated bibliography on the subject have been written in the past ten years (Demas 1999), but the field is so new that much of the recent research is unwritten or in thesis or dissertation form. And almost without exception, published research pertains to the preservation of organic materials, namely wood, in anoxic, waterlogged environments, or it discusses the backfilling of mosaics and painted surface finishes. As with shelters, much of this literature, although not specific to earthen architecture, is germane. Another avenue of research has addressed the impacts of burial on artifacts (e.g., the compression and destruction of fragile artifacts, type and rate of deterioration in the burial environment, movement of artifacts over time). Very few publications address research into the burial of earthen architecture, although the intervention is often included in general discussions of preservation options and is deemed very effective (Alva Balderrama and Chiari 1995; Chiari 1985; French 1987; Galdieri 1981; Stevens 1984).

The exceptions are a few case studies on burying earthen test walls, low above-ground walls, or sites (Agnew 1990; Calarco 2000; Caperton 1990; Matsikure 2000). One article provides a good description of the backfill design used to protect earthen plasters (Silver, Snodgrass, and Wolbers 1993), and two studies detail the reexcavation of previously backfilled earthen plasters to evaluate the effectiveness of burial (Chiari, Burger, and Salazar-Burger 2000; Dowdy and Taylor 1993). Empirically it is understood that burial is effective, and there is general agreement on the types of materials to be used: salt-free, clean, fine sand or vermiculite against a mural, or expanded clay pellets over mosaics; sandy loam or other compactible material for the main body of fill (also free of salt and organic matter); plastic netting or geotextiles as horizon markers, stabilizers, fill separators, or root barriers; perhaps rubber membranes or less permeable fill on the top layer to prevent or reduce moisture entry into the system; geodrains within the fill to provide subsurface drainage if necessary; landscaping of the fill to facilitate drainage; and revegetation with carefully selected native plants.

But it has been repeatedly noted that there are no real data to support these assumptions, and that while backfilling and burial may provide the optimum environment for long-term preservation, guidelines and characterization of that environment have not been established (Nordby, Taylor, and Propper 1988; Podany, Agnew, and Demas 1994). The purpose of backfilling or reburial is to stabilize the environment. How significant is the use of different types of fill or different types of geotextile? Is it important to use fill similar in composition and permeability to the natural fill at the site, and is that a direct function of the amount of water present? At what depth and at what rate is equilibrium achieved, or is it achieved at all? Does the use of a less permeable layer on the top of the fill reduce the amount of surface water infiltration or prevent the evaporation of groundwater? Does it matter?

Future research should be directed toward quantifying the effects of different backfilling materials and designs on the archaeological remains and their effectiveness at stabilizing the environment. This can only be done through extensive monitoring of the pre- and post-burial environment, and the pre- and post-condition of the resource. Both experimental earthen test wall programs and site-specific studies can be used to collect this information. Other research may compare a number of sites with similar environments or with quite different environments. Distinctions should also be drawn between temporary burial (e.g., between excavation seasons) and more permanent burial, for which different kinds and amounts of backfill materials and methods may be used. Perhaps the most rigorous, scientific approach has been taken for investigating the burial environment of waterlogged wood (Caple 1994 and [1996?]; Caple and Dungworth 1997; Corfield 1996 and 1998), and the methodology employed in these studies could be used as a model for investigating drier environments.

At some sites, walls may be only partially buried or backfilled in order to protect parts of the resource while allowing for visitation and interpretation. In addition to the research outlined above, the publication of conservation and engineering studies into the effects of partial backfill and methods for mitigating the problems that arise would also be of use. In particular, methods for reinforcing earthen walls of varying construction and for reducing the load on walls imparted by unequal levels of fill deserve further study and elaboration.

Once a wall or a site is buried, it cannot be assumed that all problems are solved. A monitoring and maintenance plan is essential, the compass of which is determined by the burial or backfill design. Demas and colleagues provide an excellent example (Demas et al. 1996), but more must be written on the design, implementation, and effectiveness of such plans.

Site stabilization is closely allied to burial, and, in fact, the stabilization of the burial fill may become an issue as some sites age. The most common topics in the stabilization literature are revegetation to control surface erosion and more elaborate structural interventions to control stream bank or shoreline erosion (Demas 1999; Koerner 1988; Thorne 1999; U.S. Army Corps of Engineers, Waterways Experiment Station, Environmental Impact Research Program 1989). Although rarely describing an earthen site, the literature is well developed and pertinent. Because the situation at each site is unique, it will be useful to continue publishing case studies, particularly of earthen archaeological sites when possible.

Removal and Relocation

Architectural elements have been removed from sites under the guise of archaeology since the birth of the field; important fragments were frequently relocated to museum settings. Earthen sites were, of course, more difficult to disassemble and move than stone or other masonry, and removal was largely confined to unique or valuable elements, such as painted murals, bas-reliefs, and other decorated work. But with the growing recognition in the past century that much of the value of an architectural element lies in its context, along with improved methods for preserving architectural elements in situ, removal is increasingly rare and only practiced as a last resort.

But many archaeological sites are a complex stratigraphy of building periods or cultural periods or even different cultures. After extensive documentation, destruction of upper levels is often necessary in order to continue excavation, reveal earlier levels of occupation, and understand the history of the site. As an alternative to destruction, the removal and relocation of architectural elements may be possible. While there is ongoing research in the field, only one publication was reviewed that presented the problems and potential solutions of moving and relocating earthen architectural elements larger or heavier than a decorated surface finish (Chiari, Invernizzi, and Bertolotto 1993). Further research and publications on the potential and the practicability of this alternative are warranted.

Monitoring and Evaluation

The performance of past interventions is often used to define and develop new conservation projects, but critical evaluations of those interventions are published only rarely (Chiari 1990a and 1990b; Chiari, Burger, and Salazar-Burger 2000). In addition to the monitoring and evaluation outlined above for specific interventions, the publication of site-specific treatment evaluations is warranted. As well, comparative research should be conducted that evaluates a specific material or intervention employed in a wide range of earthen sites or climates or, conversely, that evaluates different types of interventions applied in similar sites or climates. Such a critical review of past research efforts would provide invaluable information and perhaps justify the trends, or illuminate the misconceptions, of the field.

Maintenance

Although maintenance has been discussed for most of the archaeological site interventions mentioned above, the importance of designing, implementing, and periodically evaluating a comprehensive site maintenance plan cannot be overemphasized. Occasionally maintenance plans are presented or discussed in the literature (Brown, Sandoval, and Orea M. 1990; Crosby 1983a and 1983b; Gamboa Carrera 1993; Reed et al. 1979), but considering the importance of the topic, there is much more to say. Additional site-specific studies would be welcomed, as would a critical and well-documented assessment of existing maintenance plans for earthen archaeological sites, with conclusions about why they have or have not been successful in terms of preservation, management, and economics. At this point, most archaeologists, conservators, and site managers are aware of the importance of maintenance, but more distant managers and funding agencies apparently are not. Well-documented studies that stress the economic advantages of maintenance, in comparison with the more common treat-and-abandon approach, may help bolster arguments for increased legislative and financial support.

Education

The recognition of the importance of archaeological site conservation has resulted in the development of philosophy, policy, methods, and materials for achieving that end, and thus has led to the increasing specialization of the field. Education in the theory and practice of archaeological site conservation is now paramount, in order to provide a strong foundation for students and practitioners and, of equal importance, in order to allow continued exploration of the possibilities and the limits of the field. At existing academic and training institutions, topics relating to the conservation of archaeological sites might be added to or expanded in the curricula; the special requirements of an earthen site would form an important subtext. The development of new curricula would apply not only to conservation and historic preservation programs but to archaeology and anthropology programs and to specialized engineering and architecture programs as well. Short courses or continuing education programs on regional or international approaches to archaeological site conservation (such as the PAT courses—the Curso Panamericano sobre la Conservación y el Manejo del Patrimonio Arquitectónico Histórico-Arqueológico de Tierra—held in part at Chan Chan, Peru) would benefit those already working in the field. Increased efforts at education will facilitate the dissemination of information and the increased dialogue so critical to the success of the field.

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Modified Earthen Materials

By Anne Oliver

Modified earthen materials are used to create more durable mortars, patches, plasters, and renders, as well as new structural elements like adobe blocks. Modifiers may be inorganic, natural organic, or synthetic organic materials, and include additives like sand or fibrous materials that reduce shrinkage (and perhaps increase strength and abrasion resistance), stabilizers that reduce the reactivity of the component clays through sorption, adhesives that bond soil particles together, hydrophobic materials that prevent water from reaching the clays, and combinations thereof. Modifiers may also affect other properties of the earthen material, whether good or bad, such as color, reflectance, abrasion resistance, compressive and tensile strength, rigidity, water vapor permeability, and coefficient of thermal expansion.

Earthen materials have been modified for use in architecture since the earliest times, most commonly with the addition of inorganic materials like sand, lime, and gypsum but also with a wide range of natural organic materials. Thus, many conservation interventions involve characterizing the original materials and replicating their composition to the extent possible. Additional research and comparative studies have provided a greater understanding of the physical, mechanical, and chemical properties of the modifiers and modified soils. Following is an overview of the published research relating to the development, execution, and evaluation of modifiers and modified earthen materials, as well as suggestions for future research to complement, supplement, or redirect these efforts.

Published Literature

The published literature pertinent to modifiers and modified earthen materials is similar to that for nondecorated earthen materials (see "Conservation of Nondecorated Earthen Materials," p. 108). However, publications that provide relatively comprehensive discussions of modified earthen materials deserve notice. Books on new earth construction provide thorough accounts of building materials and methods, including both traditional and modern modifiers (Deng 1985; United Nations Centre for Human Settlements 1986; Houben and Guillaud 1984 and 1994; Minke 2000; Smith 1982). More specifically, Viñuales (1981) and Warren (1999) discuss the use of modified earthen materials for the repair of prehistoric or historic architecture. And publications on soil stabilization from the fields of soil science and engineering are also quite relevant, although results must be carefully evaluated and adapted for use in architectural conservation (Armbrust and Dickerson 1971; Armbrust and Lyles 1975; Nelson and Miller 1992).

Characterizing and Duplicating Original Materials

Much recent research has focused on the characterization and duplication of both original materials and original methods of preparation, many of which involve modifiers. Most publications present research into the historical use of earthen materials in a specific location or region, whether for the sake of historical knowledge (Chagas 1993; Deng 1985; Galdieri 1995; Gallego Roca et al. 1993; Menicali 1992; Šrámek and Losos 1990; Steen 1971; Stevens 1985; Viñuales 1981) or to advocate the continued use or revival of those materials and techniques (Biancifiori 1994; Casal Iglésias 1990; Ceballos 1990; Cuchí 2000; Minke 2000; Smith 1982; Zhu 1985). And a few studies describe research and analysis specifically designed to duplicate original materials and methods of preparation for use in conservation interventions (Alva Balderrama and Teutonico 1985; Mazar 1999; Skibinski 1990a and 1990b). Such research is invaluable for understanding history and culture and for designing interventions, and it should continue in the future. However, research methodologies and analytical techniques are quite variable, if indeed they are mentioned at all, often rendering results incomparable or of uncertain value. The adaptation of a standardized set of research and evaluation guidelines (e.g., American Society for Testing and Materials 1990), and the implementation of all or part of the guidelines as they suit each project, would help to make diverse research projects more comparable and thus more useful to the field.

While the identification of inorganic modifiers is well developed, and analytical techniques are easily adapted to earthen architectural materials, identification of organic modifiers is more problematic. Natural organic materials break down over time and may be present only in trace amounts or in altered forms, if at all, in aged materials. Methods for identifying organic elements have been adapted from other fields, and further development of these techniques and their increased application to earthen architecture would help to answer some historical questions and substantiate accounts about the use of a wide and sometimes strange variety of organic materials.

Inorganic Modifiers

Inorganic products are by far the most common modifiers for earthen materials. Sand is the most prevalent additive, and it may affect many of the physical and mechanical properties of the soil, like color, texture, shrinkage, compressive strength, resistance to erosion, and so forth. The effects of different grain size distributions, shapes, and proportions of sand in relation to various types of clays have been relatively well researched, and they deserve further consideration only in unusual circumstances. Other inorganic modifiers discussed in the literature include gypsum (hydrated calcium sulphate) and other salts, lime (calcium carbonate) and hydraulic lime, cement, and magnesium hydroxide.

Gypsum has long been employed as a soil stabilizer that chemically bonds with reactive clays and also creates a crystalline network that adds rigidity and strength; it is still used in drier climates today. Warren (1999) provides a review but, as he notes, "There is no published understanding of the performances of many different types of soil in the presence of gypsum sulphate and its derivatives, particularly in respect of the different types of clays, whose crystalline behaviour is likely to be modified by even small amounts of calcium sulphate capable of entering solution" (Warren 1999, 114). Several Chinese authors (Zheng 1985; Zhu 1985) report the use of salt or salinized soils for rammed earth construction to create more durable walls and roofs. The salts are not identified, but they may be calcium sulphate. The use, role, and effectiveness of gypsum and other salts as soil stabilizers, both in the past and in the future, deserve further scrutiny.

Calcium carbonate also has a long history of use as a soil stabilizer, whether through the intentional selection of calcite-rich earths for construction or through the addition of lime in its various manufactured forms (quicklime, lime putty or hydrated lime, natural cement, or hydraulic lime). It is less soluble than gypsum and is appropriate for use in many parts of the world. Cement displaced lime for several decades, but the recent predominance of reporting on lime in the literature indicates a resurgence in its use, and lime is perhaps the most commonly used stabilizer for earthen architecture today. Several publications report on the use of lime by ancient cultures (Deng 1985; Politis 1993), and Warren (1999) provides a more general discussion on its historic and contemporary use and on the properties of lime as a stabilizer for earth. Other articles are more site specific and may evaluate different types of lime or other products as potential stabilizers for a single soil (Matero 1996; Morales Gamarra 1985) or evaluate the same type of lime for different soils (Mendoça de Oliveira and Santiago 1993). For earthen architecture, recommended proportions of lime are usually 10% or less. The use of hydraulic lime is increasingly popular; as a weak cement, it cures more quickly, cracks less, is less sensitive to conditions of application and cure, and thus is often more durable than quicklime or hydrated lime (Gallieri 1993; Matero 1996; Palma Dias 1993; Šrámek and Losos 1990). Other authors advocate the addition of pozzolanic materials to calcium hydroxide (hydrated lime) to create a hydraulic lime, which can then be used as a soil stabilizer; pulverized fly ash (PFA) and brick dust are two such additives (Baradan 1990, 1993a, and 1993b; Nelson and Miller 1992; Warren 1999).

Also of great value, and usually of greater scientific rigor, are publications on the use of lime as a soil stabilizer for foundation and pavement engineering (Basma and Tuncer 1991; Little 1987; Nelson and Miller 1992). Roth and Pavan (1991) evaluate the use of both lime and gypsum stabilizers for acidic tropical soils. An interesting article by Martinez-Ramirez and colleagues presents the development and testing of a new lime mortar (for stone) that incorporates a biocide carried on sepiolite clay, and it may have application to earthen materials threatened by biological growth (Martinez-Ramirez et al. 1996). But in general, the use and effectiveness of lime as a stabilizer for earth is acknowledged and understood. Limited field testing is, of course, necessary for each specific site, but a more comprehensive scientific evaluation of different manufactured limes mixed with a wide range of clay types and grain size distributions could help to define general guidelines for the use of lime in particular situations. Admittedly, laboratory testing of nonhydraulic limes is often difficult because of the time required for cure, but Mendoça de Oliveira, Santiago, and d'Affonsêca (1990) report on a useful system developed for the accelerated carbonation of lime-stabilized soils.

Cement, portland cement in particular, has been a popular soil stabilizer for the last fifty years. It is more durable and less sensitive to conditions of cure than quicklime and hydrated lime and is stronger than hydraulic lime. When used in high proportions, cement is incompatible with earthen materials, and its color, hardness, and lack of flexibility (which often leads to erosion of surrounding unmodified materials and cracking of modified materials) and soluble salt content lead to the failure of many cement-stabilized soils. But these failures provide a better understanding of the limitations of cement, and it is still commonly used today, with good results, when used in proportions ranging from 5% to 10% (Chiari 1985; Cuchí 2000; Fagundes de Sousa Lima and Puccioni 1990; Olivier, Mesbah, and Adam 1990; Palma Dias 1993), although proportions up to 15% are advocated in certain instances (Atzeni, Massidda, and Sanna 1993). Again, Warren (1999) provides a good general discussion in relation to earthen architecture and Nelson and Miller (1992) in relation to foundation and pavement engineering.

Further research and experimentation with other inorganic materials may lead to new alternatives for soil stabilizers. For instance, Xeidakis (1996a; 1996b) has reported in an engineering geology journal on the potential of brucite (magnesium hydroxide) as a stabilizer for a wide range of clays. He states that magnesium hydroxide is internally adsorbed while calcium hydroxide is not, and the former produced more stable clays than the latter. However, a combination of magnesium hydroxide and calcium hydroxide produced the most stable clays, a finding that opens the field not only to new materials but also to new combinations of materials. In a study applied to new earthen architecture, Burtea and Georgescu (1993) experimented with combinations of primers (applied prior to mortars) and stabilized earths to develop the optimum composition of mortar for stabilized bricks in Romania. Primers included lime milk, laitance, a mixture of cement and polyvinyl acetate, and a mixture of cement, sand, and polyvinyl acetate. Soil mortars were stabilized with cement, lime, and hydrated lime. The concept of a primer—particularly when a new earthen material (e.g., a plaster or render) is applied over an old earthen material and detachment is a potential problem—is an interesting topic that deserves further research.

Natural Organic Modifiers

As with inorganic modifiers, natural organic modifiers have a long history of use. However, because many of these materials are relatively fugitive and often cannot be detected in weathered materials, information on their precise nature and use is often more anecdotal than factual, particularly when the tradition of using those materials has been lost. Natural organic modifiers include fibrous additives like straw, chaff, reeds, and hair; proven stabilizers like asphalt and bitumen; postulated stabilizers like plant mucilage; and water repellents like vegetable oils and animal fats. Since the late 1980s, the use of natural organic resins and oils as modifiers for new earthen materials has received increased attention. They are attractive not only for functional but for philosophical reasons, in that they may be part of a past or present local tradition.

The bulk of the literature on natural organic modifiers provides an overview of materials that reportedly have been used in ancient cultures. Warren (1999) provides a general summary of natural organic materials: bitumens and asphalts; natural resins like copal, wallaba resin, shellac, gum arabic, and rosin; plant oils like linseed oil; resins suspended in plant juices (mucilage) made from the agave, tuna cactus, locust bean tree, and banana plant; and animal products like blood, dung, and termite saliva. Ceballos (1990) reports the use of banana, coco, nopal, cactus mucilage, honey, milk, and rice starch in Guatemala. Deng (1985) reports the use of oil, animal fat, and glutinous rice to add water repellency to soils in China, and Palma Dias (1993) cites the use of cow dung, oils, blood, and algae elsewhere. Galdieri (1995) notes the historical use of straw, rice chaff, reeds, goat hair, and bitumen in earthen construction, while Smith (1982) mentions the use of blood, straw, and molasses in New Mexico. Sengupta (1971) describes the ancient use of bitumen for waterproofing in India. The most thorough overview of a region is provided by Politis (1993), who discusses soils and traditional stabilizers in the Jordan rift valley: "The most common is fibrous vegetable matter as a tempering agent and soil stabilisers such as calcium carbonates or asphalt [also ash]. Other additives whose properties and attributes have not yet been clearly determined include urine, animal and human hair, sap, animal blood, animal milk and various plant juices" (Politis 1993, 388).

One of the few articles to fully document and evaluate a traditional natural organic modifier is provided by Biancifiori (1994), who describes the manufacture and properties of sarooj. This is a traditional plaster used in Oman for restoration, the manufacture of which involves taking clayey earth, baking flat cakes in the sun, burying the cakes and lighting a pyre of palm trunks, grinding the ash and clay residue to form a powder, and then mixing this with water to make sarooj. The end product is partly organic and partly inorganic and is reportedly similar to a hydraulic cement because the high firing produces calcium silicates. More efforts of this nature are required to bring the use of natural organic modifiers out of fable and into fact.

Asphalts and bitumens are extremely effective soil stabilizers and have been used since ancient times; Warren (1999) summarizes their use and properties, which are well established. Asphalt- or bitumen-stabilized earths are very common in new construction (Smith 1982; Warren 1999) but less common as repair or preservation materials because, even in very small proportions, the modifier discolors the soil. In one instance, bitumen was proposed for use where earthen repairs were masked behind stone facings (Orazi 2000), while in another instance an earthen render stabilized with asphalt emulsion was applied as one of a number of test panels (Taylor 1988; 1990). Objections center around the discoloration rather than the performance of the material, and research that leads to a lessening or neutralization of the color change would be welcome indeed.

Much of the recent research on organic modifiers has centered on the use of plant extracts, particularly cactus mucilage. In Peru, earthen mortars modified with 5% tuna cactus mucilage performed well after three years of weathering, although later it was determined that retreatment with mucilage was required twice a year (Hoyle 1990). A good comparative study of earthen plasters modified with cactus mucilage, pods from the locust bean tree, banana stalks, and asphalt emulsion demonstrated that the moisture resistance of the cactus plaster was comparable to a plaster modified with 4% asphalt emulsion. The study also established the optimum soaking time for the cactus, as well as the optimum proportions of sand and straw (Heredia Zavoni et al. 1988; Vargas Neumann et al. 1988). Another study that had less positive results compared earthen plasters modified with 50% or 100% agave juice with plasters modified with a wide range of other materials, including acrylic emulsion, asphalt emulsion, and vinyl polymers (Taylor 1988; 1990). Burned olive waste has also been evaluated as an alternative modifier for earths (Attom and Al-Sharif 1998). A number of publications from the fields of soil science, soil biology, and agriculture provide insight into the stabilizing effects of some plant extracts. In an agricultural journal, Saag and colleagues have determined that cactus mucilage is composed of polysaccharides, which have a role in the storage of moisture in the cactus but which are also known soil stabilizers (Saag et al. 1975). For instance, scleroglucan, a fungal polysaccharide, has strong water-stabilizing effects on kaolinite and montmorillonite (Chenu 1989; Chenu, Pons, and Robert 1987). Theng (1974; 1979) also describes the stabilizing effects of polysaccharides. And Politis, in his excellent overview of soils and traditional stabilizers in the Jordan rift valley, points out that “tempering soil with fibrous vegetable matter such as grass, straw, or even dung serves as an adhesive, binding adobe bricks together, distributing cracking more evenly or even preventing it altogether, and assists in evaporation of moisture from the interior. The fermentation of these organic materials induces certain microbial products like extravacellular polysaccharides which are known to bind soils together” (Politis 1993, 389).

But a long list of questions must be answered before the role of natural organic modifiers (excepting asphalts and bitumens) in the preservation of earthen materials is understood. For instance: Have they actually been used historically in the ways reported? What are their chemical compositions? What are the necessary or best methods of preparation? How do the modifiers interact with different types of clays and soils? How is their performance affected by clay type or soil texture (grain size distribution)? How long do they last, how do they deteriorate, and are they cost-effective in relation to alternative materials? What are the other natural organic modifiers that may be effective but have yet to be considered? Given their potential effectiveness, availability, and relatively low cost—in addition to the philosophical appeal and the potential for continuing or reviving local traditions and perhaps investing a community in its earthen architecture—natural organic modifiers certainly deserve further scientific research into all aspects of their properties and performance.

Synthetic Organic Modifiers

Synthetic organic modifiers are used in dilute proportions in earthen mortars, patches, plasters, and renders to increase durability. Their primary advantages are stability and long life in comparison with natural organic materials, known and controlled compositions, and the fact that they rarely alter color or texture as asphalts, bitumens, and inorganic modifiers do. Warren (1999) provides a very generalized discussion of synthetic organic materials.

The most common and most successful synthetic organic modifiers for earthen materials are acrylic emulsions, usually copolymers of ethyl acrylate, methyl methacrylate, and/or ethyl methacrylate, that are diluted and used in proportions of 15% or less to avoid undue changes in soil properties, especially water vapor permeability (Atzeni, Massidda, and Sanna 1993; Morales Gamarra 1985; Selwitz 1995). The emulsions may function as adhesives that bond soil particles together, rather than binding through sorption and stabilization of reactive clays. The most thorough examination of acrylic emulsions is contained in a monograph by Hartzler (1996), who examines the use of acrylic-modified earthen mortar for repairing sandstone masonry walls, conducts laboratory analyses and characterization of in situ mortars and proposed replacement mortars, and makes recommendations for improvements to mortar mixes. More studies like this, which thoroughly examine and evaluate a soil modifier (or a consolidant or water repellent or any other type of intervention) used for a specific purpose (the requirements of a mortar may be different from those of a render) are needed. Vinyl polymers, namely polyvinyl acetate and polyvinyl alcohol, have also been used as soil stabilizers, although most commonly in agricultural or engineering contexts (Stefanson 1973; Theng 1979). For the repair of earthen architecture, Hoyle (1990) reports the use of wall caps made with soil and 5% or 10% polyvinyl acetate.

A comparative study by Taylor (1988; 1990) examined the long-term performance of modified earthen renders applied to adobe test walls. Modifiers included acrylic emulsion, a polyvinyl acetate/vinyl acetate-dibutylmaleate copolymer, asphalt emulsion, agave juice, a latex acrylic, and straw. The weathering patterns and erosion of the modified renders were visually compared with one another and with an unmodified control over a period of twenty years, with the acrylic-modified panel giving the most satisfactory performance. Another comparative study conducted by the U.S. Bureau of Reclamation and its Russian counterpart also has relevance to earthen architectural materials. Zhordania and colleagues stabilized soils with polyvinyl acetate emulsion, acrylic copolymer emulsion, asphalt, and urethane liquid and then evaluated their compressive strength, resistance to water erosion, and resistance to weathering (Zhordania et al. 1982–83). The best laboratory results were achieved with polyvinyl acetate, while in the field, both polyvinyl acetate and acrylic emulsion performed well. Urethanes gave the best resistance to weathering, but toxicity was a problem. Comparative studies like these are always interesting and useful, although they are strengthened by an analytical evaluation of the function and failure of each modifier (describing its interaction with the soil and not just its external weathering characteristics) and the precise methods for measuring change and deterioration over time.

In soil science and engineering, polyacrylamides and polyamides have also been used as soil stabilizers (Carpenter 1986; Theng 1979); their applicability to earthen architecture requires further study. Several publications in soil science also provide excellent explications of the interactions of clays and organic materials, synthetic and natural (Jasmund and Lagaly 1993; Lagaly 1984 and 1987; Theng 1974 and 1979; Tributh and Lagaly 1991). The process of transfer and application of this knowledge to the preservation of earthen architecture has not been made, and it will require close interaction among practicing professionals in both fields, as well as an expansion in the education of new conservators.

Monitoring and Evaluation

The published literature on monitoring and evaluating modifiers and modified earthen materials is similar to that for nondecorated earthen materials, and recommendations for further research are the same (see "Conservation of Nondecorated Earthen Materials," p. 108). Again, the creation of and adherence to a set of guidelines—not only for monitoring and evaluation but for the selection and use of a modifier in the first place—will help to prevent ineffective or even harmful interventions and make the results of different projects comparable. For instance, the *ASTM Standards on Soil Stabilization with Admixtures* (American Society for Testing and Materials 1990) outlines a complete set of standard tests for the identification, analysis, and evaluation of soils and the use of numerous admixtures for stabilization. It provides specifications for inorganic stabilizers and asphalt stabilizers, and one test provides a comprehensive guide for the testing and evaluation of the effectiveness of new modifiers for improving the engineering properties of soils. This might serve as a solid foundation for a set of guidelines on selecting, monitoring, and evaluating modifiers for earthen architectural materials.

Conclusion

A great number of modified earthen materials have been proposed over the years for the protection of earthen walls, and a few have been rigorously analyzed and evaluated. The effectiveness of lime, cement, asphalt, bitumen, and acrylic emulsions has been established conclusively in the field, although different methods of preparing and applying the modified materials, differences in soil composition, and environmental conditions during and long after treatment affect the durability of the interventions. But a wide range of additional research projects could be designed to test other modifiers, different application parameters, and different weathering environments. While empiric, comparative studies of several known modifiers are often all that can be afforded by individual projects, there is a much greater need for well-developed analytical and quantitative research projects. Ideally, these would seek to limit all but one set of variables at a time and would provide a thorough characterization and evaluation of modifiers and modified earthen materials through time. As with interventions for nondecorated earthen materials, once we have a better grasp of the specifics, we can make more effective generalizations.

Conservation interventions are used and evaluated in three sets of circumstances: in the laboratory, on test walls constructed in the field, and in situ on original structures at earthen sites. In much of the literature, some combination of the three approaches is reported. But while laboratory research and test walls are valuable and necessary for understanding potential interventions and also for preventing the wanton application of unproven treatments to ancient materials, there is often a discrepancy between the results obtained when consolidants are applied to new (laboratory) versus old (in situ) materials. This discrepancy may be due to differences in the properties of new and aged adobe, the heterogeneity of in situ materials, microclimates, methods of application in uncontrolled conditions and on irregular surfaces, and so forth. Further investigations into the reasons for these differences may help improve the design and results of laboratory research and experimental test walls. For example, Binda and colleagues constructed test walls, applied treatments, and subjected the walls to artificial weathering modeled on a specific site (Binda et al. 1995). The treatments were then applied to the site, and based upon those results, the design of the test walls was adjusted to more accurately reflect the environment at the site and thus render all subsequent tests more useful.

Soil composition and clay mineralogy must also be considered in any study. For instance, the general parameters of particle size distribution for a good adobe (50%–75% sand and 9%–28% clay) are well understood, but slightly different soil compositions may perform better with specific modifiers. Certain acrylic emulsions perform best in soils with at least 60%–65% coarse sand and 10%–15% clay (Hartzler 1996, 53). While most publications at least characterize the soil composition, this usually is not connected in a meaningful way with the selection and performance of the interventions. Large gaps remain between soil science, chemistry, and preservation; thus, professionals from each field must work closely together to produce coherent publications that recognize the philosophy and limiting factors of conservation, the potential of chemistry and polymer science, and the complexity and reality of clay mineralogy.

Other modifiers that might be tested include new or improved chemical products that have been adapted and tested in the laboratory for their appropriateness for use, as well as proprietary products specifically designed for use on earthen materials. Natural organic materials deserve much more investigation and research under controlled conditions. And the role and effectiveness of natural and synthetic fibers (straw, chaff, reeds, hair, nylon, etc.) require further research.

Different preparation and application parameters could also be tested, including variations in slaking or wetting time of the modifier or modified soil; preparation and prewetting of the substrate; conditions of cure (humidity, temperature, duration); application techniques (smooth troweling, rough troweling, hand application, sponge application); and so forth. The variables to be tested would be dependent on the properties of the modifier, including its intended use. Whether the material is to be used as a mortar, a structural element, a thin plaster, or a thick render will play a critical role in determining its composition, method of application, and long-term performance. Intensive monitoring of the microclimate in and adjacent to intervention would provide insight at application and throughout the process of deterioration.

Combinations of materials could be tested that incorporated the use of a stronger material at wall tops and bases, where deterioration is often most severe, and a weaker material (which would probably be more materially compatible) on the wall faces. Another example is the use of two layers of modified materials coatings, such as an acrylic-modified soil followed by a hydrophobic spray (Selwitz 1995), a soil slurry followed by a lime plaster (Rua, Rajer, and Mostacedo 1993), or a modified render with a large proportion of coarse aggregate in the bottom layer (to reduce shrinkage cracking) and a smaller proportion of aggregate in the outer layer (to increase water repellency) (Heredia Zavoni et al. 1988). Such treatments may initially be more costly but may pay off in the working life of the intervention and in reduced maintenance costs.

The maintenance and retreatment of earthen architecture with modified materials has received very limited consideration in the literature (Hoyle 1990). Because conservation is a specialized field, it is often outside consultants who design and implement treatments for a site. While many design a maintenance plan as well, they have very little control over its implementation and little opportunity to evaluate its effectiveness. In some instances no maintenance occurs, and this has obvious disadvantages. But most earthen structures are maintained, and the impact this has on the original materials—not only physically but also aesthetically, as different hands do slightly different things over time—requires evaluation. Retreatment may involve the application of the same materials or of entirely new materials, and the extent to which the old treatment affects the new is another field open for study.

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Conservation of Nondecorated Earthen Materials

By Anne Oliver

Conservation interventions for nondecorated earthen materials is a broad topic and encompasses much of the preservation work conducted today. Nondecorated earthen materials include all of the original components of an earthen construction (e.g., adobe, clay lump, cob, rammed earth, daub, and any associated mortar), excluding plain or painted original plasters, renders, bas-reliefs, high reliefs, and so forth, which might require specialized interventions and which are discussed separately in the literature review (see "Conservation of Decorated Earthen Surfaces," p. 124). Conservation interventions include cleaning and desalination and the use of grouts, consolidants, adhesives, and surface coatings for treating original materials. They do not include the use of admixtures or soil stabilizers for repair, nor do they include interventions employed mainly at archaeological sites, such as capping, shelter construction, and reburial (see "Conservation of Earthen Archaeological Sites," p. 80). Following is an overview of the published research relating to the development, execution, and evaluation of interventions for nondecorated materials, as well as suggestions for future research to complement, supplement, or redirect these efforts.

Published Literature

Most of the published literature pertinent to interventions for nondecorated earthen materials is contained in conference preprints and proceedings, most importantly in the publications that arose from the series of international conferences on earthen architecture held in Lima, Peru, in 1983 (ICCROM, Regional Project on Cultural Heritage and Development UNDP/UNESCO, and National Institute of Culture [Peru] 1985); Rome in 1987 (Rockwell et al. 1988); Las Cruces, New Mexico, USA, in 1990 (Grimstad 1990); Silves, Portugal, in 1993 (Alçada 1993); and Torquay, England, in 2000 (English Heritage, ICOMOS-UK, and University of Plymouth Centre for Earthen Architecture 2000). Additional relevant papers were written for more regional preservation conferences (Ecole Nationale des Travaux Publics de l'Etat, Vaulx-en-Velin, and Université Jean-Moulin-Lyon III 1987), for conservation conferences not specific to earthen architecture or even architecture (particularly those sponsored periodically by the American Institute for Conservation of Historic and Artistic Works [AIC] and the International Institute for Conservation of Historic and Artistic Works [IIC]), and also for conferences in allied fields, particularly clay mineralogy, soil science, and geotechnical engineering. But, as noted elsewhere in the literature review, conference preprints have inherent drawbacks. They are generally not subjected to peer review, and fail to provide adequate information about specific research so as to make it relevant to the field at large and/or to make it replicable.

General overviews of the field, ranging from brief articles to monographs, provide historical perspective and summarize the established norms for the conservation of nondecorated earthen architecture (Alva Balderrama and Chiari 1984 and 1987; Chiari 2000; Stevens 1984 and 1985; Stubbs 1995; Taylor 2000; U.S. National Park Service, Preservation Assistance Division, Technical Preservation Services 1978; Torraca 1976; Viñuales 1981). A number of books also contain information specific to the preservation of nondecorated earthen architecture (Ashurst and Ashurst 1988; Bullock 1976; Clifton 1977; Menicali 1992; Skibinski 1991; Torraca 1982; Warren 1999). Although relatively rare, site-specific reports or in-depth case studies can provide a good overview of the preservation philosophy and conservation techniques employed, and sometimes provide an evaluation of their effectiveness (CRATerre and Ecole d'architecture de Grenoble 1989; Plenderleith, de Beaufort, Voûte, and ICCROM 1964; Chiari 1975). Publications related to training workshops in earthen architecture and site conservation can also be useful (ICCROM, Regional Project on Cultural

Heritage and Development UNDP/UNESCO, and National Institute of Culture [Peru] 1985).

Books on modern earthen construction often document traditional technologies and describe materials, traditional and otherwise, for repair and conservation (Centro de Investigación de Técnicas y de Materiales Autóctonos y de Construcciones Experimentales 1986; CRATerre and Doat 1983; Universidad de Chile 1983; Houben and Guillaud 1984, 1986, and 1994; Minke 2000), although interventions for new earthen materials may not always be appropriate or effective for aged materials. Books on clay mineralogy and soils can provide comprehensive discussions not only on the properties of different clays and soils but on the interactions between clays and organic polymers, of great relevance for many of the treatments discussed here (Jasmund and Lagaly 1993; Nelson and Miller 1992; Theng 1974 and 1979; Tributh and Lagaly 1991).

Professional journals devoted to the conservation of cultural property provide a reliable and accessible forum for the dissemination and discussion of conservation interventions for nondecorated earthen architecture (e.g., *APT Bulletin, Conservation and Management of Archaeological Sites, Journal of the American Institute for Conservation, Journal of Architectural Conservation, Studies in Conservation*). Because of the broad scope of these journals, relevant articles are published infrequently; the exceptions are special issues devoted to the subject of earthen architecture (e.g., *CRM* 22, no. 6 [Barrow and Taylor 1999]). Scientific journals from related fields, particularly soil science, clay mineralogy, hydrology, and geotechnical engineering, may also contain pertinent information or articles (Armbrust and Dickerson 1971; Armbrust and Lyles 1975; Murphy 1982).

Other important resources are bibliographies that focus on earthen architecture (Barnes 1975; George 1973; ICCROM 1981; Getty Conservation Institute 2002; Odul 1993). Also of potential utility is the Gaia Project Research Index (Dassler et al. 1993), a database of current research projects in the field of earthen architecture that is maintained at ICCROM.

Cleaning and Desalination

All aspects of the cleaning and desalination of nondecorated earthen materials require further research. No references to cleaning were noted in the published literature (aside from references to removing biological growth, which are discussed elsewhere), which begs the question: Is it ever necessary to clean earthen materials? Does "dirt" get dirty? One example might be at archaeological sites. The boundary between original material and subsequent fill is usually clear, and accretions of fill can be carefully removed by hand, but in some instances encrustations have formed, and it may be desirable to remove them.

The accumulation of soluble salts is a much more common, almost pervasive, problem. While the mechanisms of salt decay and drainage methods to prevent the accumulation of additional salts are well reported (and discussed elsewhere in the literature review), only three articles mentioned methods for removing existing salts. Removal methods included manually brushing and cleaning surface deposits and applying various poultices to extract subsurface salts (for decorated surface finishes, Silver 1990 and Silver, Snodgrass, and Wolbers 1993) and leaching salts by sprinkling the walls with water (for nondecorated materials, Plenderleith, de Beaufort, Voûte, and ICCROM 1964). Methods for removing salts from stone are better researched, but these are usually water-based methods and are not always directly transferable to earthen materials.

Where salts are present in earthen materials, deterioration is often advanced, and consolidation is necessary prior to any attempts at desalination. What are the effects of salts on the performance of consolidants, do the consolidants immobilize the salts, or is desalination possible after consolidation? These questions have been researched for alkoxysilanes and acrylics used for stone conservation, but they deserve further attention in relation to other conservation materials and in the context of earthen architecture.

Grouts

The development of cracks and voids in earthen architecture is most often the result of damage from water infiltration, wall settlement, or seismic activity. It is a common problem and one of the most threatening deterioration conditions because it may compromise structural integrity. To address the problem, the compromised areas may be dismantled and reconstructed, or alternatively, a mechanical system may be installed to provide structural reinforcement. Grouts may be used to fill the cracks or cavities and reintegrate the original components of the structure, and they can be used alone or to supplement a mechanical system.

Cracks and cavities are pervasive, but the literature on grouts for nondecorated earthen materials is quite limited. Thus, it probably does not reflect the amount of work being conducted in the field. In contrast, the literature on grouts for decorated surfaces (plasters, renders, murals) is more extensive. In most instances, grouts must be lightweight to reduce the load on the bond between surface finish and substrate. They may also be required to create a bond between dissimilar materials (e.g., a lime plaster and an earthen substrate). Grouts for decorated surfaces are discussed in "Conservation of Decorated Earthen Surfaces" (p. 124).

Warren (1999) provides a general summary of grouts for earthen materials and states a strong case for the use of pulverized fly ash. The literature also discusses grouts for nondecorated materials developed to address a problem at a specific site. While the basic properties of grout were commonly accepted (low water content, adequate thixotropy, low shrinkage, low soluble salt content, mechanical properties similar to original material, no settlement prior to setting), the specific composition of the grout was the focus of each study. In each case the solution was similar: the grout was composed primarily of soil with the addition of a stabilizer to reduce shrinkage, increase strength, and possibly promote adhesion. Stabilizers included bentonite and lime (Fagundes de Sousa Lima and Puccioni 1990), hydraulic lime (Nardi 1986), lime and fly ash (Roselund 1990), and a very fine-grained and stable "mercula" clay (Sharma, Gupta, and Kanotra 1995). In all cases the grout was equal to or slightly greater in hardness than the original earthen material. A technique for grouting was well elaborated in one publication (Roselund 1990), and practices are probably rather uniform: fine cracks are filled with syringes, while larger cracks and voids are filled with a low-pressure pumping system.

But the effectiveness of grouts for the repair of earthen architecture deserves further evaluation. One purpose of a grout is to fill cracks and voids in order to prevent further infiltration and damage by water, and this it usually does. But often another purpose is to reestablish structural integrity by readhering the separated parts of the structure. Research into the degree of adhesion between grouts of varying composition and the original earthen material would be useful, as would research into methods for improving adhesion by prewetting, whether with water, polar or nonpolar organic solvents, surfactants, or adhesive substances like acrylic emulsion. An evaluation of the long-term effectiveness of grouts would also be of interest, particularly in situations where the cause of the problem (e.g., seismic activity) was not removed or could not be removed.

Consolidants

As defined by Warren, "A consolidant acts at the near-molecular level by fixing or inhibiting the capacity for movement between very small particles, thereby altering the characteristics of the material in terms of its behaviour, particularly in the presence of water. It tends to make the material stronger in compression and tension, and may affect inherent characteristics such as heat and sound transmission and rigidity" (Warren 1999, 127).

Consolidation is the most widely discussed and studied treatment for nondecorated earthen materials (excluding the use of admixtures and soil stabilizers, discussed elsewhere). Consolidants for earthen materials that are mentioned in the literature can be grouped into three broad categories based upon the chemical composition of the raw materials from which the end product is derived: inorganics (alkaline silicates), natural organics (plant mucilage), and synthetic organics (alkoxysilanes, acrylic resins, vinyl acetate polymers, epoxy resins, polyurethanes).

Water, often in combination with soluble salts, is typically the cause of the granular disintegration that consolidants are used to treat. With historic or inhabited earthen buildings, it is usually possible to reduce the impact of water by maintaining or modifying roofs, foundations, and drainage systems and by renewing protective plasters or renders. Thus, consolidants are primarily used for earthen archaeological sites and ruins, where roofs, foundations, drainage systems, plasters, and renders may be compromised or absent. In addition, the structures may be partially or fully subterranean or may be constructed into a cliff face or rock outcrop. At such sites, the success of a consolidation treatment is a complex function of the properties of the consolidant itself, the composition and clay mineralogy of the earthen material, and the degree to which the treated material can be separated from the causes of deterioration. In the exposed and relatively uncontrolled environment of an archaeological site, the long-term performance of a consolidant is highly variable.

Inorganic Consolidants

The use of inorganic materials for the consolidation of earth is limited to alkaline silicates (Dayre and Kenmogne 1993; Huang et al. 1990; Li 1990; Taylor 1988 and 1990). Warren provides a good summary:

> For consolidation, potassium silicate is preferred to the cheaper but similar sodium silicate because it does not produce surface scum or efflorescence. Although success in its use as an earth consolidant has been described, it is clear that the process depends on careful and knowledgeable execution backed by skilled analysis. The results have yet to

> be proven by extensive field trials and sustained weathering. The methods of application are straightforward and the materials are simple and readily available. Furthermore they produce in the consolidated earths an inorganic structure comparable to the formation of the soils themselves without the inherent problem of complex organic compounds liable to biological attack and breakdown. . . .
>
> [But] promising results have only been obtained under carefully calculated conditions of material preparation and circumstances of application. For some time to come the process is likely to be confined to significant archaeological material where the work is supported by a fully equipped laboratory service, as the results are dependent upon careful control and the determination of precise molar ratios in the solutions. (Warren 1999, 120)

Natural Organic Consolidants

Since the late 1980s, the use of natural organic resins and oils as consolidants, surface coatings, or additives to new earthen materials has received increased attention. They are attractive not only for functional but for philosophical reasons, in that they may be part of a past or present local tradition. As Warren notes, "The relevance [of this new interest] is not so much in the availability of the material itself but in the circumstance that the conservator chooses to use traditional methods in conservation operations and seeks to apply modified native lore to the repair of vernacular buildings" (Warren 1999, 130). A wide variety of natural organic materials have been proposed or applied to earthen materials, including bitumens and asphalts; natural resins like copal, wallaba resin, shellac, gum arabic, and rosin; plant oils like linseed oil; resins suspended in plant juices (mucilage) made from the agave cactus, tuna cactus, locust bean tree, and banana plant; and animal products like blood, dung, and termite saliva (Heredia Zavoni et al. 1988; Warren 1999). Most of these materials are used as surface coatings or additives for new earthen materials (see "Modified Earthen Materials," p. 97).

The only natural organic material to undergo scientific evaluation for use as a consolidant for in situ materials is cactus mucilage (Beas Guerrero de Luna 1993; Hoyle 1990). Consolidation appears adequate, and other changes in the properties of the earthen materials are minimal. But the treatments may age very rapidly and thus require frequent retreatment and a great investment of time. Given their potential effectiveness, availability, and relatively low cost—in addition to the philosophical appeal and the potential for continuing or reviving local traditions and perhaps investing the community in the earthen architecture—natural organic consolidants certainly deserve further scientific research into all aspects of their properties and performance.

Synthetic Organic Consolidants

No product satisfies all of the criteria for an ideal consolidant, but the alkoxysilanes arguably come closest (Alva Balderrama and Chiari 1984 and 1987; Chiari 1985 and 2000; Viñuales 1981; Warren 1999). Depending on chemical composition, alkoxysilanes may function as consolidants, water repellents, or both; their primary limitation is that they cannot consolidate grains larger than coarse sand. In the beginning, "Professor A. V. Hoffman in 1861 proposed to a meeting of architects in London the use of 'silicic ether' for the conservation of stone. The material remained rare for half a century until its use for stone consolidation was patented in 1926. Its use in earths has taken place since World War II" (Warren 1999, 121). Under the advocacy of Giacomo Chiari and others, alkoxysilanes have been used on earthen materials with increasing frequency since the late 1960s. The literature amply reflects this: of the fifty-three publications pertaining to consolidation that were reviewed, forty-five discussed the use of alkoxysilanes as a past, present, or future treatment. And in the past thirty years, the most commonly used products have been tetraethoxysilanes (ethyl silicate and poly[ethyl silicate]), which consolidate, and methyl trialkoxysilanes (methyl triethoxysilane and methyl trimethoxysilane), which both consolidate and provide water repellency. Grissom and Weiss (1981) have compiled a fully annotated bibliography on the use of alkoxysilanes for art and architecture conservation from 1861 through 1981; it pertains mainly to stone, but earthen materials are also mentioned. A more topical discussion of alkoxysilanes and many other consolidation treatments for earthen materials is provided by Warren (1999).

Because of their proven effectiveness and widespread use, alkoxysilanes serve as the standard by which other treatments are judged. Nearly all of the research publications compare the performance of alkoxysilanes with one or more alternative consolidants: alkaline silicates (Dayre and Kenmogne 1993), acrylics (Beas Guerrero de Luna 1993;

Helmi 1990; Morales Gamarra 1985), diisocyanates (Agnew, Preusser, and Druzik 1988; Agnew 1990; Coffman et al. 1990; Coffman, Selwitz, and Agnew 1990; Coffman, Agnew, and Selwitz 1991; Selwitz, Coffman, and Agnew 1990), vinyl acetates (Hoyle 1990; Morales Gamarra 1985), soluble nylon (Morales Gamarra 1985), and natural organic materials, primarily cactus mucilage (Beas Guerrero de Luna 1993; Hoyle 1990). The consolidants and the consolidated earths are usually tested for one or more critical properties: depth of penetration, evenness of distribution and linking, effectiveness with a specific clay type or grain size distribution, porosity and permeability, water absorption, resistance to water, resistance to salt, tensile and compressive strength, ease and practicability of application method, aging, and so forth. While alkoxysilanes do not always produce the strongest, hardest, most weather-resistant earths, they are commonly deemed the most effective treatments because they are the most compatible with earthen materials.

Researchers have also focused on the use of alkoxysilanes in combination with one another and with other materials, whether in sequential applications or in mixtures. Applications have included consolidation and hydrophobization with a mixture of ethyl silicate and methyl triethoxysilane (Chiari 1988); consolidation with ethyl silicate and readhesion with an acrylic polymer (Chiari, Burger, and Salazar-Burger 2000); consolidation with alkaline silicates followed by consolidation and hydrophobization with methyl triethoxysilane (Huang et al. 1990); consolidation with ethyl silicate or a mixture of ethyl silicate and methyl triethoxysilane followed by the application of an acrylic-modified earthen render and a water repellent (Selwitz 1995); and consolidation with acrylic polymers followed by consolidation and hydrophobization with alkoxysilanes (Šrámek and Losos 1990).

Acrylic resins are commonly used as adhesives, but in several instances they have also been used as consolidants for earthen materials. Those used for consolidation include copolymers of ethyl methacrylate and methyl acrylate, sold as Acryloid or Paraloid B-72 (Morales Gamarra 1985; Šrámek and Losos 1990); butyl methacrylate, sold as Acryloid or Paraloid B-67 (Beas Guerrero de Luna 1993); and copolymers of methyl methacrylate and butyl acrylate (Helmi 1990; Šrámek and Losos 1990). Acrylic dispersions, primarily ethyl acrylate/methyl methacrylate copolymers (sold as Primal AC-33 and Rhoplex E-330), have also been used as consolidants (Koob, Rogers, and Sams 1990; Morales Gamarra 1985), although they have more commonly been used as additives to new earthen materials. Most of the studies report either that acrylics were ineffective consolidants or that alkoxysilanes were more effective. Because acrylic molecules are large, resins must always be applied in very dilute solutions of organic solvents to achieve adequate depth of penetration, but they must also be applied in sufficient concentrations to ensure consolidation. As well, the physical and mechanical properties of acrylics are quite different from those of earthen materials, and acrylic polymers must be applied in sufficiently low concentrations to limit changes in the properties of the earthen materials, particularly color and reflectance, vapor permeability, and thermal properties. However, Šrámek and Losos (1990) report good consolidation and good depth of penetration of an acrylic polymer (at least 7 cm) at 5% in xylene. In situ polymerization of acrylic monomers is another option (Warren 1999). Further research and manipulation of acrylic systems may result in good consolidants that are stronger than alkoxysilanes. But it will be difficult to surpass the ease, availability, relatively low cost, and consistent performance of alkoxysilane treatments under a wide variety of conditions.

Polyvinyl acetate has received only limited use for the consolidation of earthen materials, and with poor results (Hoyle 1990; Morales Gamarra 1985). But Theng (1979), in a book on the formation and properties of clay-polymer complexes, states that polyvinyl alcohol and polyacrilamide are good stabilizers for soil, probably as admixtures for new materials rather than consolidants for in situ materials.

Acrylic and polyvinyl resins are ineffective for the consolidation of damp or wet materials, but alkoxysilanes (Chiari, Rigoni, and Joffroy 1993) and epoxies have been used with reportedly good results (Binda et al. 1995; Kwiatkowski 1984). In an interesting corollary that may have implications for consolidating damp or wet earths, Murphy (1982) studied three methods of water removal prior to impregnation with a resin for image analysis. Acetone replacement of soil water was the best method for preventing contraction and shrinkage of pores during drying, and thus preventing subsequent difficulties with resin impregnation.

An extensive and carefully designed research project examined the use of diisocyanates and alkoxysilanes for the consolidation of adobe walls (Agnew, Preusser, and Druzik 1988). Preliminary laboratory research involved the application of the consolidants to samples of adobe from around the world and to manufactured soils, which resulted in the conclusion that clay mineralogy and grain size distribution play significant roles in the effectiveness of the treatments (Coffman et al. 1990; Coffman, Selwitz, and Agnew 1990; Coffman, Agnew, and Selwitz 1991). Test walls were constructed at Fort Selden, New Mexico, USA, and were consolidated with diisocyanates and alkoxysilanes of various concentrations and by different methods of application. The walls were then subjected to accelerated weathering and were carefully monitored (Agnew 1990; Selwitz, Coffman, and Agnew 1990). Although it is not yet finalized, the general conclusion appears to be that diisocyanates consolidate as well or better than alkoxysilanes, producing a wall of nearly rock-like hardness, but only with specific clay mineralogies and specific (and perhaps problematic) methods of application. Whatever the ultimate results, the comprehensive nature and rational methodology of the study are among its most important aspects. Research projects of this nature are rare because of the great investment of time and money required, but efforts should be made to sponsor more such studies to answer a well-formulated set of questions in a very thorough way.

General Comments

It has been amply demonstrated that consolidants, especially alkoxysilanes, work well in a wide range of situations and in a variety of combinations, but research projects are difficult to compare because the same baseline information is not provided, treatment methods are not adequately described, and evaluation criteria and methods vary widely. The common type of ad hoc research on these materials has reached the end of its useful life. The creation of a standardized set of research guidelines (a sort of expanded set of ASTM or RILEM tests) and the implementation of all or part of the guidelines as they suit each project would help to make diverse research projects more comparable and thus more useful to the field. Guidelines might vary for projects conducted in the laboratory, on test walls, and in situ, but not greatly.

The role of the solvents that are used to carry consolidants is often not considered in conservation research and interventions. Admittedly, there is little choice of commercial products, and the specialized knowledge necessary to create a mixture with alternative solvents is often not available. Warren (1999) provides a good general discussion of solvents, but more specific research is necessary into the performance of the same consolidant used with different solvents on different types of clays and soil mixtures.

The preexisting condition of an earthen material, the microclimate in and around it, and the conditions of application during treatment impact the initial effectiveness and long-term durability of the consolidant. For example, Chiari, Rigoni, and Joffroy (1993) investigated the application of ethyl silicate in damp conditions and determined that the consolidant works well when applied to dry material that subsequently gets wet, but it is less effective when applied to wet material. High concentrations of soluble salts may also render treatments with alkoxysilanes less effective (Kumar and Price 1994). In another example, conditions of application were modified, and surface migration of a consolidant was controlled by wrapping walls in gauze wetted with glycerine (Huang et al. 1990). But the impacts of preexisting conditions, microclimate, and application conditions deserve further research.

The way in which consolidants age and fail in earthen materials is not well researched. Attempts to evaluate in situ performance are few and are confined to the alkoxysilanes, and they rely almost entirely on visual observations (Chiari 1990a and 1990b; Chiari, Burger, and Salazar-Burger 2000). Several laboratory studies have gone further by examining the degree of hydrolysis of alkoxysilanes over a period of four years (Lewin and Schwartzbaum 1985) and examining changes in microstructure with scanning electron microscopy over a period of sixteen months (Chiari 1988). But as researchers point out, estimates of loss of strength and effectiveness are difficult because laboratory and field conditions are not the same. By identifying the rate and manner in which consolidants fail under various circumstances, it may be possible to modify critical materials and conditions and thus prolong the life of the treatment. As well, the impacts and effectiveness of retreatment with the same consolidant or another conservation material are very poorly researched and deserve further investigation, particularly as the numerous treatments applied over the past thirty years continue to fail in the coming years.

Adhesives

Chemically, there is no clear boundary between a consolidant and an adhesive. A very dilute adhesive material—e.g. an acrylic resin in organic solvents—might be termed a consolidant, while the same material in a less dilute form might be termed an adhesive. The difference is largely functional: an adhesive is used to bridge gaps between grains larger than coarse sand, and it may be used to consolidate extremely friable earthen materials (where a consolidant would be ineffective), to bridge a narrow crack, or to bridge a void in order to reattach one sound piece of earthen material to another. In contrast, a consolidant acts at a near-molecular level to penetrate deeply and fix grains smaller than coarse sand. The use of adhesives is common on stone and fired masonry but is a relatively rare and often inappropriate treatment for nondecorated earthen materials. The materials are inherently weak, and an adhesive might bond only a very narrow margin of earthen material to a very narrow margin on the other side. The adhesive would solve the immediate problem of detachment, but the surrounding material would be prone to shear around the repair. In such circumstances, more structural interventions are required, such as mechanical systems that provide support for the mass of material. The use of adhesives as consolidants is limited to special circumstances, because the high adhesive concentrations required tend to cause unacceptable changes in the properties of the treated material, which may also affect the weathering of the surrounding untreated material. Understandably, adhesives are much more common with decorated surfaces where a thin layer is readhered to a more massive substrate or where consolidation of highly friable materials is imperative (see “Conservation of Decorated Earthen Surfaces,” p. 124).

Surface Coatings

Surface coatings for nondecorated materials can be categorized as either hydrophobic materials, sealers, or sacrificial coatings, but their fundamental purpose is the same: to increase the water resistance of earthen materials. As with consolidants, surface coatings can be divided into inorganic, natural organic, and synthetic organic materials. Products may be transparent or opaque, but in most cases they are extremely thin, pellicular layers that are contained at the surface of the earthen materials. Sacrificial coats like lime-based and cement-based renders may be somewhat thicker. Surface coatings are attractive because they preserve the physical appearance of the earthen materials and do not greatly obscure the articulation of the aged material.

Books on new earthen construction provide the most complete discussion of surface coatings and present both traditional and modern products, the advantages and disadvantages of those products, different application and finishing techniques, methods for testing coatings, and so forth (Houben and Guillaud 1984, 1986, and 1994; Minke 2000). But weathered material behaves quite differently than does new material, and the information in these books must be used with caution or even disregarded in some instances. Unfortunately, the body of information on surface coatings for weathered earthen materials is less organized and incomplete, presented largely as case studies in conference proceedings or journal articles.

Inorganic materials like lime, gypsum, and cement are commonly used as sacrificial coatings. Lime and, to a lesser extent, gypsum are traditional coatings in many parts of the world, and their past use for both plasters and whitewashes has been well documented (Boxall and Trotman 1996; Mold 2000; Houben and Guillaud 1986; Stevens 1985; Zhu 1985). Many additives can and have been incorporated in these materials to strengthen or alter specific properties; these include linseed oil, tallow, skim milk, whey, casein glue, animal glues, and mineral fillers (Houben and Guillaud 1986). Lime and gypsum were displaced to a large degree by the advent of cement-based coatings in the twentieth century, but the failings of this material are well known, and lime especially has seen a resurgence in recent years (Dayre and Kenmogne 1993; Mold 2000; Rua, Rajer, and Mostacedo 1993). Nardi (1988) reported great success with a sacrificial slurry coating of limewater and sifted clay. Alkaline silicates have also been tested as surface coatings (Taylor 1988 and 1990).

Natural organic coatings have a long history of use—in particular linseed oil, asphalts, and bitumens (Taylor 1988 and 1990; Warren 1999). The latter were “originally applied as hot tars, then as cold tars in solvents, and currently as water emulsions compatible with the cold tar base” (Warren 1999, 129). Natural resins (copal, wallaba resin, shellac, gum arabic, and rosin) and resins suspended in plant juices (mucilage made from the agave cactus, tuna cactus, locust bean tree, and banana plant) have also been used or proposed, although whether as surface coatings or as additives to new earthen materials is not always clear (Casal Iglesias 1993; Heredia Zavoni et al. 1988; Warren 1999).

In the past thirty years, a wide range of synthetic organic surface coatings has been tested on earthen materials, and treatment histories at some sites provide a vivid illustration of the evolution in theory and products (Robbins 1983). The trend has been away from sealants and toward breathable water repellents and sacrificial coatings. The most widely used and effective water repellents over a range of conditions are the alkoxysilanes, which may be applied as water repellents or as part of a consolidant–water repellent mixture (Wacker or Conservare Stone Strengthener H) (Šrámek and Losos 1990). An aqueous acrylicfluoric dispersion has also been tested (Skibinski 1990a; 1990b), as have commercially available acrylic and polyvinyl acetate dispersions (Taylor 1988; 1990). For sacrificial coatings, several experimenters have employed a latex or acrylic modified soil slurry, which is sprayed in a very thin coat over the earthen material (Ferm 1990) and perhaps then sprayed with an alkoxysilane water repellent (Selwitz 1995).

But as Warren notes, although the use of synthetic resins has been studied and documented, "no researcher would claim that the use of synthetic resins in conservation of earth structures is at other than an early stage of study" (Warren 1999, 131). Empirical observations are certainly of value, and two such studies have extensively evaluated the performance of a range of surface coatings on test walls (Dayre and Kenmogne 1993; Taylor 1988 and 1990). But there is no published scientific information describing the physical and chemical interactions between earthen materials and surface coatings used for conservation, particularly natural and synthetic organic materials. Books from the soil sciences on the interaction of clays and organics provide a solid foundation (Theng 1974 and 1979; Tributh and Lagaly 1991), but this information needs to be distilled and applied more directly to the conservation of aged earthen materials.

Understanding the interactions of clays and soil structures with both organic and inorganic materials is fundamental to evaluating the existing array of surface coatings, improving their performance, and developing new alternatives. Also, unusual surface treatments that have been developed for stone conservation might find application for earthen materials, including reaction inhibitors for reactive clays and crystal growth inhibitors to reduce the damage caused by soluble salts (Price 1996). And while many protective coatings are not appropriate for use as long-term coverings for standing adobe walls, a few might have other applications that should be considered (e.g., for temporary protection of archaeological excavations).

Variations in preparation and application parameters also require research, including variations in slaking or wetting time of the surface coating; preparation and prewetting of the earthen substrate; conditions of cure (humidity, temperature, duration); application techniques (smooth troweling, rough troweling, hand application, sponge application, spray application, bulk infiltration); and so forth. The variables to be tested would be dependent on the properties of the surface coating. Intensive monitoring of the microclimate in and adjacent to the area under investigation would provide insight at application and throughout the process of deterioration. And maintenance of surface coatings is critical because they are so thin, although this is often overlooked. Thus the effects of retreatment with both the same and different materials, particularly the organics, become important, and there is no research to date that addresses this issue.

Monitoring and Evaluation

Monitoring and evaluation are critical to assessing the effectiveness of a conservation treatment and determining the need for maintenance or retreatment—and also perhaps for rationalizing the permanent alteration of original materials and justifying cost in general. But monitoring and evaluation are often not constructed into a project design, or are only pursued for a few years until more pressing concerns arise. In many cases, an intervention is monitored only once, many years after treatment, when only the fact of failure and not the process can be noted. Test walls are often better monitored, or at least more regularly, because the process is built into the project design, and results are critical for answering the research questions that are being asked (Agnew 1990; Dayre and Kenmogne 1993; Selwitz, Coffman, and Agnew 1990; Taylor 1988 and 1990).

Most monitoring programs for treated areas involve periodic visual assessment and perhaps photographic recording, often in comparison with untreated areas (Agnew 1990; Chiari 1990a and 1990b; Chiari, Rigoni, and Joffroy 1993; Chiari, Burger, and Salazar-Burger 2000; Dayre and Kenmogne 1993; Hoyle 1990; Selwitz, Coffman, and Agnew 1990; Taylor 1988 and 1990). A few efforts have also been made to quantify performance by measuring erosion from pins set in the walls (Agnew 1990; Taylor 1988 and 1990) or, potentially, by using a laser sensor to record wall profiles (Binda et al. 1995). But in general, monitoring and evaluation must become more quantitative and thus allow comparisons among monitoring times and among different places. Research into simple but accurate and relatively nondestructive methods for doing this is recommended. Understandably, in-depth monitoring and evaluation cannot be a part of every project, but a few research projects that thoughtfully assess the effectiveness of various monitoring and evaluation systems would serve the field well.

Monitoring focuses on whether the intervention is working, but an equally important question is why. Most evaluations simply correlate rates of erosion with environmental factors, and while this is important, there is much more to learn about physical and chemical changes in the treated earthen material. Scanning electron microscopy (SEM) has been used to evaluate the physical change in treatments over time (Chiari 1988; Hartzler 1996; Lewin and Schwartzbaum 1985), and the environmental scanning electron microscope (ESEM) may prove an even more useful tool (Doehne and Stulik 1990; 1991). The evaluation of aging of conservation interventions must be studied not only with microscopy but with the vast array of laboratory tests and analytical techniques that can be adapted and directed toward answering this question.

Conclusion

The tremendous variety of earthen materials, environments, deterioration mechanisms, and potential solutions is at times overwhelming, as noted by Warren:

> The conservator is therefore left with the choice of accepting the limited ranges of proprietary materials or seeking specialist advice on the formulation of special compounds and application techniques. While specialist advice is obtainable, it tends to be derived from sources with experience in specific limited areas. There is no current professional or institutional source base for advice across the entire spectrum of earths and materials available for their consolidation. The common method of procedure is therefore to seek advice from those experienced in comparable problems—a pattern likely to persist for some time while conservation institutes and agencies gather and build upon experience. (Warren 1999, 132)

And Price's comment on the application of silanes to stone is equally relevant to the application of many conservation interventions to earthen materials:

> Although the literature contains many papers describing the use of [conservation interventions], there are very few that even attempt to come to grips with the underlying chemistry or the associated . . . technology. One gets the uncomfortable impression that few conservation scientists have the ability to utilize the extensive chemical literature in this area, and that this is preventing the transfer of valuable knowledge to the conservation field. (Price 1996, 20)

Because of the relative weakness of earthen materials and the greater reactivity of their component parts, namely clays, understanding the interactions of consolidants and earthen materials is even more important than it is for stone. The literature on clay mineralogy and the interaction of clays with organic compounds and polymers is well developed (Jasmund and Lagaly 1993; Theng 1974 and 1979; Tributh and Lagaly 1991). The gaps between soil science, chemistry, and preservation must be bridged, but it is rare to find individuals trained in or capable of transitioning between these three fields, let alone an individual capable of explicating it to preservation practitioners. Thus, professionals from each field must work closely together to produce coherent publications that recognize the philosophy and limiting factors of conservation, the potential of chemistry and polymer science, and the complexity and reality of clay mineralogy. Such collaborative research must be directed at established interventions for earthen materials and also at any new interventions that are developed in the future.

One area of promise is the use of combinations of treatments, where the sum effectiveness of the intervention is greater than its parts. Warren notes:

> Intermixtures of technique provide one of the most promising and sophisticated fields of potential, loosely describable as composite structures. Thus a soil which might be ineffectually restrained by a particular geotextile might behave entirely differently if even moderately modified by a consolidant and the combination of the two materials may be more efficient in cost and in longevity than a heavier and more expensive application of either alone. (Warren 1999, 132)

Another example is the use of two layers of surface coatings, for instance, an acrylic-modified soil slurry followed by a hydrophobic spray (Selwitz 1995) or a soil slurry followed by a lime plaster (Rua, Rajer, and Mostacedo 1993). A third example is the application of different treatments to different portions of a wall, determined by the type and rate of deterioration present in each location. Such treatments may initially be more costly, but they may pay off in the working life of the intervention. Certainly these types of treatments deserve further attention.

Conservation interventions are used and evaluated in three sets of circumstances: in the laboratory, on test walls constructed in the field, and in situ on original structures at an earthen site. In much of the literature, some combination of the three approaches is reported. But while laboratory research and test walls are valuable and necessary for understanding potential interventions, and also for preventing the wanton application of unproven treatments to irreplaceable materials, there is generally a large discrepancy between the results obtained when consolidants are applied to new (laboratory) versus old (in situ) materials. This discrepancy may be due to differences in the properties of new and aged adobe, the heterogeneity of in situ materials, microclimates, methods of application in uncontrolled conditions and on irregular surfaces, and so forth. Further investigations into the reasons for these differences may help improve the design and results of laboratory research and experimental test walls. For example, Binda and colleagues constructed test walls, applied treatments, and subjected the walls to artificial weathering modeled on a specific site (Binda et al. 1995). The treatments were then applied to the site, and based upon those results, the design of the test walls was adjusted to more accurately reflect the environment at the site and thus render all subsequent tests more useful.

Once a better understanding of the specifics is developed, it may be possible to make more accurate generalizations and simplifications in the field of conservation. Chiari states:

> I would like to see a whole series of shortcuts developed and implemented to obtain acceptably approximated values of many important magnitudes which it is at present too difficult or time-consuming to measure. This may be done at different levels: we may devise very simple tests to be done in the field . . . which of course will not give precise data, but perhaps information that is useful in practice . . . I would like to see the same thing done in the lab, with simplified procedures that would make possible a whole series of data to be collected in a cheap, quick way. (Chiari 2000, 111)

As Chiari goes on to say, one of the most important things to look forward to in the future is the standardization of such procedures as materials testing and analysis, the selection of conservation treatments, and the evaluation of those treatments. Only then can the research community produce easily comparable data, and only then can it truly profit from the efforts of individual research projects.

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Conservation of Decorated Earthen Surfaces

By Leslie Rainer

Introduction

The conservation of decorated surfaces constitutes a specialized area within the fields of earthen architecture and heritage conservation. Decorated surfaces include wall paintings and decorative painted schemes, as well as relief that can be built up, carved, and/or painted, executed over plaster or directly onto an earth support. As with other types of construction, the exterior surface often receives decoration for a variety of reasons, not the least of which is often as a protective covering of the structural support. At the same time, it is often the most vulnerable layer. Decorated surfaces may be a significant element of the building and require maintenance and likely conservation over time. Their conservation is intimately linked to the whole earthen architectural system.

While there has been a fair amount of research on earthen architecture in general, as well as on wall paintings, there is a relatively small body of research specifically focused on the conservation of decorated surfaces on earthen architecture. This is problematic, because too often in the past, wall paintings have been examined and treated without taking into account the architectural system of which the decorated surface is the presentation layer. Because many of the problems encountered in the conservation of wall paintings or other decorated architectural surfaces are connected to the structural and support layers of the building, this directly impacts the diagnosis and treatment decisions made for these surfaces. Again, these are often the most vulnerable element of the building. Earthen architectural systems are very susceptible to deterioration for a variety of reasons, and the equilibrium of the system from structure to surface is critical to the preservation of the whole. Compounding the problem is the complexity of earthen systems, in which diverse materials may be used in the different layers (Houben and Guillaud 1994; Rainer 1992). This requires that the wall painting conservator treating a decorated surface on earth must be familiar with the conservation problems of earthen architecture, so as to design appropriate treatments for the wall painting or otherwise decorated surface that take into account a holistic approach to the conservation needs of the architectural system.

Some research has been carried out, in the laboratory and in the field, relating to earthen plasters and wall paintings, and these have provided the base for conservation in this specialized area. Studies have been done on specific decorated surfaces, which can then be adapted to other cases. Much of the research done in this area has been in university settings (e.g., University of Pennsylvania Historic Preservation Program, Courtauld Institute of Art Wall Paintings Course) by organizations such as ICCROM, CRATerre-EAG, and the Getty Conservation Institute (GCI) and by national heritage organizations like the United States National Park Service.

Conference proceedings and professional publications on both earthen architecture and on wall paintings often address issues of the conservation of decorated surfaces, with some articles specifically addressing decorated surfaces on earth. Such publications include *6th International Conference on the Conservation of Earthen Architecture, Adobe 90 Preprints* (Grimstad 1990); *7th International Conference on the Study and Conservation of Earthen Architecture* (Alçada 1993); *Terra 2000: 8th International Conference on the Study and Conservation of Earthen Architecture* (English Heritage, ICOMOS-UK, and University of Plymouth Centre for Earthen Architecture 2000; and *Case Studies in the Conservation of Stone and Wall Paintings* (Bromelle and Smith 1986). In many cases, research carried out and reported is generally part of a field project and is undertaken to determine treatments for specific problems.

Therefore, specialists often depend on information obtained from related specialties, drawing from painting and wall painting conservation, as well as architectural conservation, and adapt it to their specific needs. Otherwise, they depend on extrapolating from case studies and use materials and techniques employed in similar projects, with greater or lesser success.

This discussion includes information culled from a variety of sources, and it addresses issues of documentation, deterioration, treatment, and ongoing research into the area of decorated surfaces on earthen supports. It was undertaken in part in the context of the Project for the Conservation of Wall Paintings at Mogao, Dunhuang, People's Republic of China, a collaboration between the GCI and the Dunhuang Academy. It reflects areas of focus and expertise of the author, and while it attempts to be comprehensive, there are certainly other references that could be added to this review.

General Information

As a general reference, the comprehensive volume *Conservation of Wall Paintings* (Mora, Mora, and Philippot 1984) gives full information on the conservation of wall paintings, with some reference to wall paintings on earthen supports. *Conservation of Earth Structures* (Warren 1999) provides an overview of conservation of earth structures with some case studies on treatment of decorated surfaces. Both of these books address conservation through a methodological approach, focusing on decorated surfaces as an element of the total architectural system. A comprehensive presentation of many accepted materials currently used in conservation is given in *Materials for Conservation: Organic Consolidants, Adhesives, and Coatings* (Horie 1987). For construction techniques, there is much published by CRATerre-EAG, particularly the encyclopedic guide *Earth Construction* (Houben and Guillaud 1994).

Documentation

Documentation is one of the fundamental aspects of the conservation of decorated surfaces on any support, and references on documentation practices for wall paintings will likely be relevant to decorated surfaces on earth. There are numerous references to documentation for conservation, and specifically documentation of wall paintings. These broad works provide information on the methods and materials used for conservation of these surfaces. Of particular importance is condition recording and full documentation of treatments in written, graphic, and photographic form. Mora, Mora, and Philippot present a comprehensive method of examination of wall paintings (1984). Recently, computer documentation has become more and more common, and this has been reported on in recent conference proceedings (Schmid 2000). This raises some issues, though, of permanence and usability of the information over time. With the constantly evolving field of digital recording, programs may become obsolete, and information that is meant to be useful over the long term may nonetheless be lost because of problems of translation.

Proceedings from a research seminar on graphic documentation systems in mural painting conservation (GraDoc) held at ICCROM, published in 2000 (Schmid 2000), present current trends in documentation for wall painting conservation. The papers are not specific to decorated surfaces on earth but, rather, pertain to wall paintings and architectural surfaces exhibiting painted decoration and/or relief. The main considerations regarding decorated surfaces are the accurate and legible recording of decoration providing the fullest information possible. As mentioned above, graphic, photographic, and written documentation are all important for a full description of the decorated surface condition and treatment. The more these can be correlated, the more informative the documentation will be. For large works, it is important to record the whole surface and to have the ability to zoom in on specific details. Digital documentation (CAD, GIS, and other customized systems) has recently been developed for specific application to wall paintings. This is described and discussed extensively in the GraDoc Proceedings (Schmid 2000). Two notable case studies include: a comprehensive project at Mesa Verde National Park, Colorado, in which a model was developed for digital graphic documentation of architectural finishes on earth, carried out by the University of Pennsylvania and the National Park Service (Fiero, Matero, and Rivera 2000); full documentation procedures were also developed for polychrome bas-reliefs on earth by Piqué and Rainer (1999).

Analysis of Earth and Paint Materials

The identification and characterization of materials are critical to a thorough understanding of original fabrication and deterioration processes, and they inform decisions regarding treatment and maintenance needs. Material compositions can be varied and complex in the buildup of structural support, plaster, and paint layers. Pigments and binders can be susceptible to alteration, and this can affect decisions regarding treatment of the surfaces. Since the characterization of earthen materials is discussed in another section of this review, emphasis here will be on the identification and characterization of plaster and paint materials in particular, as related to decorated surfaces—with the understanding that the surface is intimately connected to the architectural support. It is often at the interface between layers that problems may occur; thus, a thorough understanding of the support layers is required for the development of treatments for the surface.

A useful publication is the *AATA* special issue on matte paint (Hansen, Walston, and Bishop 1993). This volume lists pertinent references on the history and technology, analysis and examination, properties, and treatment of matte paints, which are often characteristic of the materials used to decorate the surfaces of earthen architecture.

The most concise and useful handbook of laboratory techniques for characterizing building materials, including earth, is *A Laboratory Manual for Architectural Conservators* (Teutonico 1986). Other references that have been used are ASTM standards, British standards, and the United States National Bureau of Standards. Analytical methods for conservation of wall paintings on earthen supports were evaluated in a recent work by Shekede (2000). Methods included particle analysis, X-ray diffraction (XRD), microscopy, and thin section analysis for earth supports; ion extraction, loss on ignition, and microscopy were used for identification of organic additives. Further study should be done on methods of analysis of pigment and binders for decorated surfaces on earth, drawing from standard analytical methods used in paintings and objects conservation; to date this link has not been sufficiently explored. Given the nature of the plasters and paints (pigments and binders) that have been used on earthen architecture, study and discussion of appropriate analytical techniques for the identification and characterization of component materials would be useful to practitioners and scientists in the field.

Several case studies have focused on the characterization of materials specific to plasters and decorated surfaces on earth. One early and thorough work was done by Smith and Ewing (1952) on the physical and material characteristics of kiva mural decorations in the southwestern United States. Other early technical studies were done on the materials in the wall paintings from Kizil (Gettens 1938) and paint/sand plasters used in the Tumacacori interior decorations (Steen and Gettens 1962). A later work on the analysis of Pueblo architectural finishes in the American Southwest was undertaken by Silver (1990). A thesis on the characterization and analysis of prehistoric earthen plasters, mortars, and paints from Mughouse, Mesa Verde National Park, Colorado (Dix 1996), outlines the different analytical techniques that can be carried out for plasters and paints at one site. Casoli and colleagues (Casoli et al. 2000) undertook a project to identify pigments and binders from earthen bas-reliefs of the ancient Manchay culture in Peru, using X-ray powder diffraction for the pigments; binders were analyzed using gas chromatography–mass spectroscopy. Pigments from painted surfaces at a Moche site in Peru were carried out by Kakoulli (1997) to better understand the materials and techniques of the painted decoration at a specific site. The results of these studies can be used as a basis for other cases.

Deterioration

Many references addressing the problems of deterioration can be found in the general literature review for earthen architecture, especially with regard to the deterioration of earthen construction materials and renders. The deterioration of paints and other finishes, though, is specific, and is not necessarily discussed in the general literature.

Many of the common problems of paint and plaster deterioration on earth are summed up by Dix (1996). She states that "the principal mechanism by which paints on earthen plaster deteriorate is the loss of mechanical strength. As a result, paints can lose adhesion to the wall . . . between layers, or internal cohesion whereby the paint disintegrates and powders. Water can also obliterate painted finishes. . . . Organic binders, if and where present, can be affected by biodeterioration, resulting in similar mechanical failure of plasters and paints" (p. 38).

Problems of pigment alteration are also of concern for wall paintings on earth. Case studies that discuss pigment alteration and color measurement of wall paintings on earth are presented in a number of papers in the proceedings of the conference "Conservation of Ancient Sites on the Silk Road" (Agnew 1997).

Other factors of deterioration are effects of previous interventions. Again, for painted surfaces in situ in fluctuating climatic conditions, the addition of surface coatings can be detrimental to the paint, plaster, and the earth fabric because of differential dimensional change of the layers and differences of water vapor permeability. Barrier films may inhibit transmission of water vapor through the various substrate layers to the surface. Though there has been extensive research on the use of surface consolidants on earth, there has been little published research carried out on this aspect. And yet such deterioration problems are evident at many sites with decorated surfaces on earth.

Preventive Measures

Often the best means of ensuring the protection of decorated architectural surfaces is a plan for preventive conservation rather than direct intervention. Such measures may include stabilization of the architecture (roof and foundation repairs, etc.), shelters, and reburial for archaeological sites. While these topics are treated in other sections of this review, they are mentioned here as a reminder that research on the conservation of decorated surfaces on earth need not focus only on direct treatment. Appropriate repairs and maintenance of the architecture, described for the Royal Palaces of Abomey (Joffroy and Moriset 1996); drainage systems; as those developed at the site of Chan Chan (Morales Gamarra 1985); shelters for exposed wall paintings; or reburial of decorated surfaces on archaeological sites as undertaken at Aztec Ruins (Silver, Snodgrass, and Wolbers 1993) may be the best options for the preservation of some wall paintings or other decorated surfaces on earth. Of course, these preventive measures may also need to be combined with treatment steps.

Treatment Testing

The testing of proposed treatment materials and methods may be carried out both in the laboratory and in the field, prior to use on the actual artifact or wall painting. However, after the design and implementation of treatments, the results of such testing often go unpublished. Even when case studies are presented and/or published, the preliminary testing phase is often not included; the literature more often focuses on treatments and their outcomes. Thus, published research in this area is lacking, and more work should be carried out both in the laboratory and in the field regarding decorated surfaces on earthen supports. While the selection of proposed treatment materials is an important aspect of testing, it must be coupled with research regarding the characterization and performance of original materials, as well as deterioration mechanisms. The difference between paintings in controlled environments, like museums, and decorated surfaces on sites that are exposed to the elements (and often to greatly fluctuating climatic conditions) makes this an important area of study. Techniques should be developed that can be used in the laboratory and in the field, if the results are to be useful for conservation and preservation of decorated surfaces in situ. Analytical techniques used in painting conservation can be adapted, as can protocols used for earthen materials. Such testing is vital for all steps of treatment, including grouting, reattachment of paint and plaster, treatment of salts, cleaning, surface consolidation, and aesthetic reintegration.

A few research projects have specifically focused on the conservation of decorated surfaces on earth. Isobel Griffin (1999) studied grouts for wall paintings on earth, investigating their working properties and performance characteristics. Research carried out through the University of Pennsylvania Historic Preservation Program has focused on and advanced treatment testing, especially for decorated and undecorated plasters and finishes on earth. A model project undertaken by the University of Pennsylvania and the National Park Service at Mesa Verde, Colorado, integrated testing in many aspects of conservation of earthen architectural plasters and finishes (Fiero, Matero, and Rivera 2000). Frank Matero and Angelyn Bass (1995) reported on testing carried out from 1991 to 1993 to develop a suitable grout for lime plasters on adobe. The performance of natural and synthetic consolidants on different plasters was tested in the laboratory for use in the field by Beas Guerrero de Luna (1993). Other work has included research into the potential of lasers for the cleaning and uncovering of wall paintings (Shekede 1997b). In studies that are related, though not specifically focused on decorated surfaces on earth, results of this type of research can be adapted for further treatment testing on these specific decorated architectural surfaces.

General Treatment

Reports on treatment, especially site-specific interventions, are common in the literature. These references are valuable in the development of treatments, but the specificity of case studies should always be taken into consideration in designing treatments, especially when considering surfaces that may be in different environmental conditions and that exhibit particular deterioration problems. The parameters and requirements for specific treatments must always be considered in context. While it is necessary to take into consideration the specific needs and problems of each case before implementing treatment, the scope and extent of published literature on case studies can guide treatment decisions. Treatment steps specifically related to decorated surfaces on earth are described below in a general order, though the order of treatment steps may differ from case to case.

Basic issues to be considered in developing treatments are, as for all conservation, minimal intervention, compatibility of treatment materials with the original, reversibility of the materials where possible, and retreatability.

Treatment of Plaster Layers

In keeping with the complexity of earthen architectural systems, different plasters have been used on earthen structures, including lime, gypsum, and earth. Some treatment materials are appropriate for one type of plaster but less appropriate for another. General literature on plaster materials can be useful in this area; however, the complexity of the earthen architectural system must be taken into consideration. This is critical in diagnosing problems and designing treatments.

Problems can occur between the plaster and the support, such as decohesion of the plaster layer and delamination between plaster layers and between plaster and paint. The latter will be discussed in the section on treatment to the paint layer(s). Decohesion of the plaster layer will be discussed in the context of surface consolidation.

Reattachment of Plaster to the Structural Support

Due to the diverse composition of materials used in building materials and plasters, detachment of the plaster from its support is a common problem warranting research.

Anchoring and Pinning

One response to detachment is the mechanical reattachment of the plaster to the support. This has been achieved by anchoring or pinning, using a variety of anchor materials, including iron or steel rods with metal or Plexiglas crosses to hold the plaster to the wall. However, these are quite rigid compared to the plaster material, and the exposed crosspiece is visually distracting and usually obscures part of the surface decoration.

Recent research into pinning techniques using modern materials has been carried out on baroque frescoes on a lime plaster over a clay and straw ceiling, using a flexible polyamide screw inserted through the lime and clay/straw layers, and attached with a type of molly in the ceiling. This system is reported to function well (Schorer 1997).

Earthen rivets have also been used to reattach wall paintings on earthen plaster on a rock wall. This consists of inserting an extruded hard earthen or plaster bar into a predrilled hole through the plaster layer and to the support, pressing with the proper force, and leaving it to set. In this report, the earthen or plaster bar was amended with polyvinyl acetate (PVAC) emulsion (Qi 1984).

Grouting

In the past twenty years, grouts have been tested and developed for the reattachment of plasters to their supports. These are usually liquid mortars with adhesive properties, which are designed to fill gaps between the plaster and support layers. Early work in developing injection grouting using a liquid hydraulic lime mortar was carried out by Ferragni and colleagues for ICCROM in the early 1980s for mural paintings and mosaics (Ferragni et al. 1984). This work has remained the basis for further development of grouts for lime and other materials. In his recent book, *Conservation of Earth Structures*, John Warren (1999) gives an overview of materials that can be used for grouting on earthen architecture.

Research carried out in the southwestern United States has looked at grouts for lime plasters on earthen architecture (Matero and Bass 1995). A degree thesis by Bass (1998) presents a thorough study for the design, testing, and evaluation of hydraulic lime grouts for reattaching lime plasters to earthen supports. Baradan (1990) writes about a pozzolanic mixture of fly ash and lime for use in conservation, and Schwartzbaum, Na Songkhla, and Massari (1986) used low-alkaline hydraulic lime, liquid lime, or PVAC for reattaching murals on earth plaster in Thailand.

Other studies have been done using cement-based grouts. Hartmann (1996) tested three grouts: a proprietary cement-based grout (Ledan), a modified cement-based grout, and the hydraulic lime grout developed by ICCROM. He encountered problems of sedimentation with all mixtures. Likewise, in an article about water-based grouts, mostly for stone buildings, Quayle (1991) presents cement-based materials and techniques for grouting. While these may not be appropriate for decorated plasters on earth, the methodology and some materials discussed might be useful for application in developing appropriate grouts for decorated plasters on earth.

In reference to grouting of adobe walls, Roselund (1990) reported the injection of modified earth for filling cracks in adobe. In this testing, the earth was modified with portland cement and/or fly ash and lime. Again, this might not be appropriate for decorated surfaces on earth, but testing procedures are fully described and could be useful in developing grouts for this purpose. Shekede (1997a) proposes the use of earth grouts for domestic wall paintings on earth, using earth similar to the original plaster, as well as a method for grouting in layers, allowing drying time between successive applications.

Microgrouting

For detachments between plaster layers or between the plaster and support, in which there is little or no void, a variety of adhesives have been used. At Mesa Verde in 1981, a pilot treatment was done using PVAC emulsion as an adhesive to reattach delaminated areas. After nine years, the treated areas remained stable (Silver, Snodgrass, and Wolbers 1993). On archaeological fragments in Jordan, which were removed from their support and remounted for museum exhibition, detached areas were treated by injecting Acryloid B-72 between the strata (Lewin and Schwartzbaum 1985). The use of such materials should be studied for specific cases if they are to be used in an uncontrolled environment with fluctuating conditions.

Detachment

Historically, detaching wall paintings from their original support and remounting them on a new support was an accepted means of preserving wall paintings, due to the risks of deterioration in situ, particularly in unstable, damp, or isolated environments. Wall paintings on earthen supports are especially susceptible to damage and deterioration and have been detached from their original walls and remounted on new supports with some success. However, this practice is no longer acceptable except in cases of imminent threat of destruction, as there is now a greater recognition that much of the value of the decorated surface lies in its intimate link to the architecture for which it was designed. Without this link, it loses much of its meaning. Fundamentally, detachment alters the very nature of the wall painting from an immovable architectural element on a wall to a movable painting/object that has lost its original context. That said, in extreme or rare instances, detachment may be justified. In such cases, there are several references on detachment and remounting in the literature (Stout and Gettens 1932; Smith and Ewing 1952; Xu 1985a; Yang 1996).

Fill Removal

Because of changing approaches and materials used for treatment over time, it may be necessary to remove fills used for loss compensation in previous treatments. Very little was found in the literature on this topic, and it appears that the most common method of removal is by mechanical means. In the case of cement-based fills in polychrome bas-reliefs, previous, unstable repairs were reduced or removed mechanically using Dremel tools and scalpels (Piqué and Rainer 1999). There is always a need in these cases to consider the surrounding original material, which often may need to be protected with a temporary facing during removal of the fill.

Filling of Cracks, Losses, and Edge Repairs

Plaster repairs are widely discussed in the literature. On fragments of wall paintings that have been detached from their original support and on wall paintings in situ that show damage, plaster repairs can be necessary for the structural integrity of the wall painting, or they can be cosmetic. In any case, it is preferable to use materials that are compatible with the original, both mechanically and aesthetically.

The literature suggests many different approaches to and materials for plaster repairs (Hanna, Lee, and Foster 1988; Gordon 1997), depending on the condition and characteristics of the original and its context. Regarding treatments of decorated surfaces on earth in situ, the trend is toward the use of compatible earth as a base for the repairs, with or without the addition of an adhesive. In the U.S. Southwest, a range of mixtures has been used. As early as the 1930s, at the excavation at Awatovi, preliminary plaster fills used plasticized calcareous sand (Smith and Ewing 1952). More recently, at Mesa Verde, edging and fills were formulated to be physically and mechanically compatible and similar in texture and color to the original, using suitable aggregates or earth (Matero and Bass 1994). Chinese case studies follow the trend of using materials similar to the original for edge repairs for wall paintings in situ. Most commonly reported are earth mixed with PVAC and sometimes natural fibers (Qi 1984; Xu 1991).

For losses in polychrome bas-reliefs in Benin, local earth, compatible with the original laterite earth used in the construction of the originals, was used (Piqué and Rainer 1999). The material characteristics of this earth made the addition of adhesives unnecessary. In Thailand, lacunae were treated with fills of the same material as the original, as described by Schwartzbaum, Na Songkhla, and Massari (1986). In Ladakh, a naturally occurring material (Mercula clay) has been used as a cementing material for construction of adobe structures. Its composition (illite, approx. 83%, with approx. 23% Al_2O_3) and properties indicate its suitability for repairs, for which about 25% Mercula clay is added to the local earth mix (Sharma, Gupta, and Kanotra 1995). This is a very localized and specific case, but it shows the advantages of careful analysis and selection of specific materials for conservation. On wall paintings in Peru, Samánez Argumedo (1986) reports that loose edges were consolidated with a mortar of fine sand and hydrated lime (2:1), with the addition of Mowilith DM1 H in water. Losses were filled with the same mixture.

For fragments that have been removed from their original sites and treated in a museum environment in China, different materials have been used for infills, among them polystyrene foam or earth (Yang 1996). Fragments from Karadong were treated in the laboratory with a mortar made of lime, sand (from Turfan), and a vinyl resin, which was used to fill gaps between fragments and edges. A final mortar was made with a color similar to that of the original for the surface finish (Joseph and Vasquez-Urzua 1995).

Treatment of the Paint Layer(s)

Deterioration of the paint layer can occur at the interface between the plaster and paint layer, or it can manifest as delamination between layers of paint or paint and ground, or as decohesion of the paint layer (powdering of the surface). It cannot be stressed enough that the complex stratigraphy of the paint, plaster, and support materials in an earthen architectural system plays an important role in decision making regarding interventions, and it should be well analyzed before treatment proceeds. The treatment of the paint layer cannot be addressed without considering the materials used for the plaster and the support, and without considering the environmental conditions for decorated surfaces in situ.

Reattachment of Flakes

The reattachment of paint flakes requires an appropriate adhesive that has the strength to adhere the paint layer back to the ground layer, that will perform well over time (that is, it will not become brittle or lose its adhesive properties), and that will not change the optical properties of the surface (by staining, changing the gloss, or discoloring pigments or colorants). Many adhesives have been used on wall paintings and decorated surfaces in the past, including natural organic glues and synthetic adhesives, depending on specific conditions. Since the paints on earth are often water sensitive and can be underbound, an adhesive that would change the water vapor transmission at the surface could adversely affect the paint and plaster layers over time, causing subflorescence or efflorescence of salts, leading to flaking, and peeling.

Traditional Materials

Regarding natural adhesives, animal glue and isinglass have been used to reattach paint flakes. In several Chinese reports, isinglass was used for reattachment of paint flakes on clay sculptures (Zhou and Zhang 1995; Wu, Zhang, and Zhou 1994). On Chinese wall paintings, a solution of animal glue and alum in water has been used in the past (Qi 1984). Qi suggests that polyvinyl alcohol (PVOH) and PVAC can replace the animal glue. In a pilot conservation program at Mug House in Mesa Verde, thin delaminations and flaking layers of wash or paint were reattached with a gelatin solution (Fiero, Matero, and Rivera, 2000). Other natural and synthetic aqueous adhesives were field-tested in the scope of this project, and the dilute gelatin was found to be most effective.

Synthetic Materials

There has been widespread use of PVAC in water, both on fragments in a museum environment (Miller, Lee, and Ellam 1987; Lewin and Schwartzbaum 1985) and on wall paintings in situ. In Peru, flaking paint has been reattached by injection using Mowilith DM1 H (Samánez Argumedo 1986). Other case studies report using PVAC in various solvents: PVAC in toluene (Singh and Sharma 1993) and loose pigments that have been fixed with a dilute solution of PVAC dissolved in toluene, alcohol, and ethylene dichloride (Sengupta 1984).

Acrylic dispersions and emulsions in water have also been used with good results, as, for example, Rhoplex AC33 on polychrome earthen bas-reliefs in Abomey (Piqué and Rainer 1999). At Aztec Ruins National Monument, an acrylic emulsion was used, and the murals have remained stable (Silver 1997). In the tomb of Nefertari, conservators used Primal AC-33 (30% in water) to reattach paint flakes to the earth plaster (Mora and Mora 1993).

Another synthetic adhesive that has been used widely in wall painting conservation is Acryloid B-72,[1] also called Paraloid B-72, in various solvents. The use of this material is widespread in wall painting conservation. It was used in Thailand on wall paintings on earth plaster to reattach the flaking paint layer by injecting Paraloid B-72 in toluene behind the surface (Schwartzbaum, Na Songkhla, and Massari 1986). In another report from Thailand, Paraloid B-72 was used; however, for some paintings with thick grounds, it was replaced with cellulose nitrate when Paraloid B-72 failed (Na Songkhla 1985). Acryloid B-72 has also been used

[1] Acryloid B-72, a methyl methacrylate produced by Rohm and Haas, is also known as Paraloid B-72. Both names can be found in the literature and are interchangeable. The name used in any given reference is used in the text here.

on some earth finishes—for example, on Pueblo architecture in the U.S. Southwest, where it was used to reattach paint flakes. This worked well unless repeated applications were necessary, and then the optical appearance would be altered (Silver 1990).

In related case studies addressing problems of underbound paint, though not on earthen supports, other adhesives have been tried. Very dilute ethylhydroxyethylcellulose (Ethulose) in deionized water and ethanol was employed as a fixative for powdering and flaking paint on tempera paintings at the U.S. Customs House (not on an earth support) (Silver 1997). Methylcellulose in water was applied as the adhesive for consolidating and reattaching gouache paint on works of art on paper using ultrasonic misters to avoid shininess or discoloration of the painted surface. The adhesive has long-term stability, good flexibility, and physicochemical compatibility with existing materials (Beentjes, van Dalen, and Marchal 1999). These case studies, though not specific to decorated surfaces on earth, could provide direction for the further study of adhesives for decorated earthen architectural surfaces.

Flaking paint on fragments of detached wall paintings remounted in a museum environment have been treated with Raccanello acrylic silane E55050 (a mixture of acrylic and silane resins in 1,1,1-trichloroethane and toluene) (Hanna, Lee, and Foster 1988). Otherwise, Beva D-8 in water has also been used for reattaching flakes (Gordon 1997).

Little evaluation of adhesives is evident from the literature. One exception regards work at Mesa Verde, in which prior treatments were evaluated. Those using water only to rehydrate the earth plasters and those using a dilute solution of PVOH in water both failed over time, as did 5% and 10% gelatin solutions injected behind delaminated or detached plaster layers. Treatments using thickened acrylic emulsion solution appeared to be successful at stabilizing loose and flaking areas of plaster and washes (Rivera and Slater 1999). Evaluation of treatments should be carried out and reported on in order to further understanding of different treatment materials and to determine their appropriateness.

Cleaning

Cleaning can be carried out using a variety of methods and materials, depending on what is to be removed from the surface. In the case of wall paintings on earthen architecture in situ, often there is a surface accumulation of dust and debris. Further buildup can be in the form of soot, stains, biological growth, coatings, and overpaint, which may each require different levels of cleaning and removal.

Traditional methods and materials include mechanical removal, dry cleaning, water-based systems, and solvent mixtures; these are prevalent in the research literature. Advanced cleaning techniques that have been under recent development include aerosols, dry cleaning methods, solvent gels, resin soaps, enzymes, and laser cleaning; however, there was little mention of them in the literature reviewed. As is often the case in conservation, there is always a need for research that explores alternatives using gentler, nontoxic systems over toxic materials.

Removal of Surface Accumulation

Cleaning of surface accumulation is often a primary intervention. In the literature, different methods are described, though water-sensitive paints on earth may likely be cleaned by dry methods. These can include removal of surface debris by vacuum (Bandaranayake 1997) or careful dry dusting using a pen knife and a soft brush (Smith and Ewing 1952) or, in one case, a kneadable eraser (Luk et al. 1997).

Carefully used, water-based systems can be employed. In all mentions of aqueous cleaning on water-sensitive paints on earth, cleaning was done using a damp swab (Na Songkhla 1985; Piqué and Rainer 1999) or done through a poultice, as was done in Thailand, using compresses of paper pulp and ammonium carbonate (Schwartzbaum, Na Songkhla, and Massari 1986). In Peru, Samánez Argumedo (1986) reports using a combination of mechanical and water-based systems with bicarbonate of soda in water using a swab. Singh and Sharma also report using a mixture of water, ethylene glycol, ethylene dichloride, and triethanolamine, followed by a thorough cleaning with a mixture of methyl alcohol, Cellosolve, and ethylene glycol (Singh and Sharma 1993). Such water-based systems must always be tested before use because of the sensitive nature of earthen materials. The method of application and removal is often as critical as the choice of materials to be used for treatment. Richard Wolbers gives an overview of water-based systems for cleaning in his book *Cleaning Painted Surfaces: Aqueous Methods* (Wolbers 2000).

Soot Removal

Soot can be derived from smoke of different derivatives—greasy soot from cooking, wood fire, or burning of various plants. Therefore, when it is appropriate and desirable to remove it, the complex formula of the soot deposit can be challenging. On a given surface, there may be problems in completely removing the soot layer and/or in removing it without harm to the underlying paint layer, especially on an earthen support. Many different materials have been used for soot removal, most using toxic solvents or solvent combinations. In his work on conservation techniques for Chinese mural paintings, Xu (1985b) suggests that soot can be removed by using a solution of toluene, butyl alcohol, and butyrolactone lactate (1:2:2). On mural paintings in a monastery in India, smoke, soot, and greasy and tarry matter were removed using a mixture of triethanolamine and methyl alcohol (1:100, with a small addition of dibutyl phthalate) (Singh and Sharma 1993). On mural paintings in Peru, soot and organic debris were removed with pyridine (Samánez Argumedo 1986). Though these treatments have been published and are included in the literature review, many of these materials are not recommended because of their toxicity. Recent advances in conservation propose alternative cleaning systems that may be as effective and yet less harmful than toxic solvent systems.

Removal of soot on two detached Ming Dynasty wall paintings consisted of a solvent-soap-gel system using xylene, benzyl alcohol, Armeen CD, Carbopol, and Triton-X. The gel was diluted with Shellsol and applied with a cotton swab and then rinsed thoroughly with Shellsol. This system acted as a soap that could break through the soot, dissolved in a solvent that would not affect the paint layer. It was noted that if this process should be used again, the Triton-X could be eliminated from the mixture and the surface rinsed with xylene, which has a higher aromatic content than Shellsol (Gordon 1997).

Stain Removal

The removal of different stains requires specific solvent formulas depending on the nature of the stain to be removed. Stains can be biological products such as molds, fungi, or excrement, or they can be chemical stains deposited on the surface. In addressing stain removal, a thorough understanding of and positive identification of the stain is advised in developing treatment for the specific case.

Xu reports removing oil marks with tetrachloroethylene and oil, wax, and lacquer with carbon tetrachloride, acetone, xylene, trichloroethylene, turpentine, and alcohol and dimethylformamide, and so on. Elsewhere oil stains have been removed with tetrachloroethylene or ammonia (Xu 1985b). Stains from wood preservative were removed from polychrome earthen bas-reliefs using acetone in poultices (Piqué and Rainer 1999).

At the British Museum, stain removal was carried out on archaeological earthen wall painting fragments using microscopic poultices of cellulose powder with a mixture of hydroxide and ammonium hydroxide, both in distilled water, stopped by distilled water (Miller, Lee, and Ellam 1987). In Peru, yellow stains on white areas were treated with Chloramine-T, a bleach (Samánez Argumedo 1986). Germicides, such as sodium pentachlorophenolate, have been used to remove mold from mural paintings. In one case where mold was treated on a Chinese wall painting, after drying, the mold spots were brushed away with a soft brush (Qi 1984). In this case, and in some other reports, a protective coating was subsequently applied to the surface.

Removal of Coatings

The removal of coatings from previous restorations is often reported, and the need for their removal indicates that a thorough evaluation of the effectiveness and longevity of coatings applied to wall paintings on earth supports is necessary before application. In most cases, the coatings have failed and have led to further damage to the original surface. Their removal can be extremely difficult, and it may not be possible to remove them entirely.

In the case of an archaeological site in the U.S. Southwest, a fragmentary wall painting was coated with shellac and cellulose nitrate, which exacerbated the problems of deterioration in an exposed environment, causing the paint layer to curl and detach from the earthen render. The coatings were removed by the application of solvent mixtures through Gore-Tex, used like a poultice, drawing the dissolved coatings out and depositing them on the surface of the tissue. Not all coating material was removed (Silver 1997).

In Singh and Sharma's work on wall paintings in a monastery in India, the old preservative coat (likely PVAC) was removed using toluene and a mixture of different organic solvents in various proportions and combinations (ethylene glycol, Cellosolve, methyl alcohol, butyl acetate, acetone, and petroleum ether), with turpentine as a "restrainer" applied with cotton swabs. A coating containing PVAC in toluene, with phthalate as a plasticizer, was then applied over the cleaned murals (Singh and Sharma 1993). In the Dambulla Rock Temple Complex in Sri Lanka, there is also mention of the removal of an old PVAC coating, though the method used is not described (Bandaranayake 1997).

Treatment of Salts

Wall paintings often manifest deterioration from salts. They can cause damage to the paint and plaster in different strata (efflorescence, subflorescence), and the damage can vary to different degrees, with a variety of manifestations. Problems include deterioration of the paint and plaster (seen in detachment and exfoliation of the paint and plaster layers), disaggregation of the earthen plaster and/or paint, crystallization of salts below the paint surface, localized losses in the paint layer, and salt efflorescence on the surface, seen as a whitish veil or as salt crystals.

There is little material directly regarding the treatment of salts on decorated surfaces of earthen structures; however, studies have been done on the treatment of salts on wall paintings on other supports. Much of this work could be relevant, and research should be directed toward wall paintings specifically on earth in the future. The outstanding question in this area remains: Is it feasible to remove salts completely from an architectural system, or from an architectural support, especially if it is inherent to the original material? Salt cycling could prove to be more risky to the system than partial removal, if the cycles continue because of environmental fluctuations. Studies to date have addressed the topic in a number of ways.

Common methods of mechanical salt removal include dry brushing (Piqué and Rainer 1999) and use of a scalpel (Torraca 1984). Surface salts have also been removed by cotton swabs moistened with saliva (Silver 1997). These methods do not attempt to desalinate the wall or the wall paintings completely but instead attempt to remove the efflorescence from the surface only, with an understanding that salts may remain below the surface. In one treatment in the U.S. Southwest, salts were removed by light brushing, then more tenacious salts were treated with compresses of paper pulp with a saturated solution of bicarbonate of soda, followed by compresses of distilled water. The author reports that 50% of the salts were removed, with no damage to the rendering or paint (Silver 1990).

Much of the work on desalination deals with testing, followed by implementation in some cases. One very interesting study was done on lime renders in an underground crypt. The testing combined surface consolidation with desalination by poulticing. Laboratory testing was carried out by first consolidating the renders. After three months of curing, compresses of Arbocel BC 1000 with deionized water were applied in three separate applications. More salt was removed with the second compress than with the first, and this was unexpected. Overall, results appeared to show better conditions after treatment testing. However, in situ test results showed that twenty times less salt was extracted than was extracted in the laboratory tests (Bläuer Böhm and Häfner 1996). This study shows that results of laboratory and field testing may differ greatly, and it is extremely valuable to carry out both and then comparatively evaluate results for realistic treatment options.

Studies have been done on desalination of objects with good results. While these studies may be used in developing treatments for decorated earthen architectural surfaces, they may not be easily adapted. An article on the desalination of earthen tablets by immersion was reviewed, and while the method is not applicable to architectural surfaces, a protocol for sample preparation is given, and a recommendation is made at the end of the article to test poultices for desalination, which could be useful for wall paintings (Liégey 1996).

In a related study, cellulose pulps and cellulose ethers were researched for use as poultice materials. The article presents the characteristics and working properties of a series of cellulose pulps and cellulose ethers used in conservation. The results showed that cellulose pulps are preferable over cellulose ethers in many cases (Redman 1999). Another article on desalination of ceramic objects had sections on the qualitative and quantitative identification and measurement (before and after extraction) of salts, with information on measurement instruments (Paterakis 1987). This kind of information is useful in designing treatment testing of salts in decorated surfaces on earthen architecture.

Detached wall painting fragments on earth at the British Museum were also treated for salt removal. The surface of one fragment was wetted with distilled water using a fine mist spray; sheets of blotting paper were laid down and carefully flattened with a soft wet brush. After twenty-four hours the poultices were removed and analyzed for salt content. The poultices were weighed into beakers of distilled water, and left to soak for twenty-four hours. The liquid was then filtered and the soluble chloride content was determined. Poulticing was repeated until the soluble content was reduced to a negligible level. The fragment was then returned to a dry, stable environment, where its condition could be regularly monitored (Miller, Lee, and Ellam 1987). Again, it is necessary to remember that this type of treatment may be suitable for wall painting fragments in a controlled museum environment, but it may not be effective for wall paintings on earth supports in situ.

One case of poulticing wall paintings in situ for salt removal is discussed in an article on the conservation of Chinese wall paintings. Compresses (poultices) approximately 5 mm thick made of paper fiber, that can also be mixed with kaolin, pumice powder (1:1), and a dilute solution of PVOH, were used for salt removal from the surface (Xu 1985b). No conclusive results of the effectiveness of this method, however, are given.

Surface Consolidation

The problems of powdering plaster and paint are common in the conservation of earthen materials, and surface consolidation seems to be among the most studied areas in the conservation of earth, since the problem of surface deterioration (decohesion), whether on bricks, plaster, or paints is common. While this is discussed in the section on plasters, some references referring directly to decorated surfaces will be discussed here. There is often an overlap in the discussion of plaster consolidation and paint consolidation, since the materials may show similar properties and problems of deterioration.

A variety of products have been tested and used in the conservation of wall paintings on earth, to consolidate powdering paint and friable earth support layers. These include naturally occurring adhesives and mucilage, synthetic organic resins, and silicone esters and silanes, which may, in different ways, act as binders for a powdering paint layer. Criteria for the selection of suitable surface consolidants are similar to those for the selection of an appropriate adhesive. There should be no visible change in optical properties (change in gloss or darkening of the surface), and no detrimental effect to the surface or substrate due to difference in strength at the surface or differential properties of water vapor transmission between the consolidated surface and the substrate.

Traditional Materials

In China, traditional materials have been used to consolidate the surface of powdering paint layers on earth renders. Most common appears to be animal glue and alum in water at different low percentages applied once or twice to the paint layer (Qi 1984; Huang 1984). The same materials have also been used traditionally for consolidation of powdering surfaces prior to detachment of wall paintings in China (Xie 1997). In one article, traditional materials for consolidation included casein and shellac, as well as the animal glue and alum in water (Xu 1982).

In a related case study using traditional materials to consolidate a tempera painting (though not on earth), dilute rabbit skin glue was applied as a fine mist (Silver 1997). The author reports that the painting has remained stable since treatment.

Synthetic Materials

Many reports show that traditional materials are being replaced by PVAC and PVOH for consolidation (Qi 1984). Treatments in China currently include use of PVAC and PVOH as consolidants (Xu 1982, 1985a, and 1985b; Yang 1996; Li et al. 1993). On wall paintings at Bamiyan, PVAC was used as a preservative layer, often applied in more than one coat but in such a way that the surface gloss was not altered (Sengupta 1984).

Many tests have been carried out at the Dunhuang Academy in China to determine various properties of different consolidants. In the early 1990s, Li Yunhe and colleagues tested the stability of PVAC and PVOH by accelerated aging and considered the effects on color alteration by these two consolidants. The conclusions of the testing show that both PVAC and PVOH have good resistance to photochemical deterioration under different levels of RH. Also, PVOH consolidation does not affect the color; however, according to their report, it can make the gypsum layer transparent and saturate the blue color (Li et al. 1993). In another study by Li and Nishira, comparative tests, conducted on twelve consolidants, looked at the properties of resistance to thermooxidization and to UV deterioration. Consolidants tested include PVAC, PVOH, potassium silicate, lithium silicate, and Paraloid B-72. Test results showed that both PVAC and PVOH have good resistance to thermooxidation and UV deterioration. They also have good penetration properties. Paraloid B-72 is reported to be more stable than PVAC and PVOH, especially under high humidity. Potassium silicate and lithium silicate were also reported to have good results. They have the advantages of stability and low cost, and they are easy to apply. No other mixtures than the ones mentioned above showed good results (Li and Nishira 1993). Su and Li carried out experiments using color monitoring instruments to measure the color change of specimens before and after PVAC, PVOH, and Paraloid B-72 were applied. Results showed that Paraloid B-72 causes more color alteration than PVAC and PVOH (Su and Li 1996). These studies give information on certain aspects of treatment on earthen decorated surfaces. However, lacking in the literature is long-term evaluation of treatments using these products in situ. This is critical for materials that have been widely used in very different and uncontrolled environmental conditions, to determine if they are, in fact, effective and successful treatment materials over time. Less published are reports on decorated surfaces on earth that exhibit deterioration after an initial treatment.

Several case studies mention the use of Acryloid/Paraloid B-72 for surface consolidation. Painted earthen plasters at Mesa Verde were preconsolidated with a solution of 3%–5% Acryloid B-72 in toluene and xylene (1:1) through a Japanese tissue facing. This did not change the color or gloss of the paint layer (Matero and Bass 1994). Acryloid B-72 was also used as a consolidant at the Dambulla Temple Complex in Sri Lanka (Bandaranayake 1997). Areas of powdering paint on earthen polychrome bas-reliefs were consolidated using 3%–5% Acryloid B-72 in acetone in localized areas (Piqué and Rainer 1999). In the tomb of Nefertari, where the original binding medium had disintegrated, causing the paint to become powdery over much of the painted surface, the wall paintings were treated with 3%–5% Paraloid B-72 in lacquer thinner (Mora and Mora 1993).

Acryloid B-72 has also been used on fragments in museums. On archaeological painted fragments, paint layers were consolidated with Acryloid B-72 (7%) in acetone (Lewin and Schwartzbaum 1985), as were fragments from Turfan (Joseph and Vasquez-Urzua 1995). A 5% solution of Acryloid B-72 in xylene was brushed over the surface of detached Ming Dynasty wall paintings to consolidate the paint layer (Gordon 1997). In the case of two Chinese wall painting fragments at the Philadelphia Museum of Art, one wall painting fragment was consolidated with Acryloid B-72 in xylene, applied in a glove bag enclosure saturated with xylene vapor. Alternatively, methylcellulose provided sufficient adhesive strength without altering the reflectance or saturation of the paint surface on the other fragment (Luk et al. 1997). Methylcellulose has also been used as a surface consolidant for gouache paints on works of art on paper, applied by ultrasonic misters to ensure small drop size and low concentration of adhesive, to avoid shininess or discoloration of the painted surface. The mister also allows for a gentle and controllable application of the adhesive (Beentjes, van Dalen, and Marchal 1999). In this case, the same treatment was used for reattachment of paint flakes.

Of the numerous synthetic consolidants currently in use, ethyl silicate has been one of the more commonly used with regard to earthen structures and surfaces and has undergone a fair amount of testing (Chiari 1990a; Lewin and Schwartzbaum 1985). In his evaluation, Chiari reports that there is no ideal surface consolidant for conservation of adobe in all cases. However, criteria for evaluation and results of different treatments are given. Various materials are evaluated, including synthetic resins and ethyl silicate (Chiari 1990a). Lewin and Schwartzbaum found that on archaeological fragments treated with ethyl silicate, the sample analyzed showed that much more hydrolysis had occurred following initial cure. Additional studies should be done to understand if this further hydrolysis creates stress on the material, or if the consolidating effect of the ethyl silicate may gradually weaken and dissipate upon prolonged aging.

Comparative product testing has been done on the consolidation of earth surfaces. In a degree thesis on the analysis and consolidation of architectural plasters at Çatalhöyük, Turkey, Kopelson tested three types of consolidants, including an epoxy resin, an acrylic resin, and ethyl silicate. Testing was done in the laboratory and in the field. Preconsolidation was done using rabbit glue or Aquazol 50/T1919, with varying results (Kopelson 1996). Beas also presents a laboratory testing program for three different consolidants on earth: plant mucilage of tuna cactus; Acryloid B-67, a synthetic organic resin; and Conservare OH, a synthetic inorganic silane. According to Beas's test results, Conservare OH performed best overall on the clay samples, though vapor transmission decreased 43% (Beas 1991). This work also gives specific technical information on various commercial products, case studies where products have been used, and evaluation of products where available.

Alkoxysilanes have also been used for consolidation. In the U.S. Southwest, friable rendering was stabilized with Tegavakon alkoxysilane (Silver 1990). The author notes that Conservare H and Conservare OH could also be tried.

Aesthetic Reintegration and Presentation

Aesthetic reintegration deals mainly with the presentation of the painted/decorated surface. One of the objectives of wall painting conservation is to render the image or the decoration legible. The decision regarding the extent of aesthetic reintegration depends largely on the specific case. In current conservation practice, there is a tendency to carry out minimal aesthetic reintegration, especially on archaeological objects, finishes, and sites. On more recent mural schemes, this may be quite different, and reintegration can be carried out to a greater or lesser degree—toning of the fill plaster, neutral tones in the losses, inpainting of damage and, in some cases, of wear.

Recent research follows this tendency toward minimal intervention, and there is, in fact, little mention of final reintegration in many case studies, implying that it may have been limited or may not have been done at all. On Ming Dynasty wall painting fragments in the British Museum, surface reintegration was done by troweling or stippling the gap filler mixture over the surface depending on the depth to be filled. Inpainting was done with acrylic paints. No surface coating was applied (Hanna, Lee, and Foster 1988). Similarly, on two other detached Ming Dynasty wall painting fragments, retouching was limited, using Flashe 1300 colors. An exact color match was avoided; losses that exposed white ground were not filled (Luk et al. 1997). Aesthetic reintegration, including surface fills of local earth, was carried out on detached polychrome bas-reliefs in Benin, West Africa, and inpainting used slaked lime and dry pigments in acrylic binder in background areas only (Piqué and Rainer 1999). Two articles on Thai mural painting also describe minimal retouching only in lacunae (Na Songkhla 1985), and the use of traditional *tratteggio* technique to distinguish reconstructed areas from the original (Schwartzbaum, Na Songkhla, and Massari 1986).

Evaluation of Treatments

There are few published evaluations of treatments on decorated surfaces on earthen supports. Giacomo Chiari undertook evaluation at several sites where ethyl silicate was used in different conditions: a backfilled site with an adobe painted frieze in Cardal, Peru (Chiari, Burger, and Salazar-Burger 2000); a damp Roman site from the fifth century BC in Feltre, Italy; Fort Selden, New Mexico; Grenoble, France (Chiari, Rigoni, and Joffroy 1993); and an archaeological site in Iraq (Chiari 1990b). The evaluation of these treatments is invaluable. Parameters for evaluation should be well defined, and the evaluations should be developed to give the most information possible if they are to be of use for other projects.

Maintenance

Maintenance is one of the most important aspects of the conservation of decorated surfaces on earthen supports in situ. Some case studies address this, such as those of the bas-reliefs at Abomey, Benin (Piqué and Rainer 1999), and the site of the Royal Palaces of Abomey (Joffroy and Moriset 1996). Little, however, is written specifically on this topic, but larger studies on site management should include reference to this, particularly when the decorated surfaces are a characteristic feature of the site.

Conclusion

There is a growing body of information on decorated surfaces on earth, though most of it involves the reporting of treatment of decorated surfaces in situ or of wall painting fragments in controlled museum environments. Testing and evaluation of materials for use specifically on decorated earthen architectural systems are also little studied. To date, practice has been primarily informed by research adapted from other fields and/or materials. Research—including analytical methods for understanding materials and their behavior, treatment testing in the laboratory and in the field, evaluation of interventions over long-term periods, and so on—specific to decorated surfaces on earth should be undertaken and, equally important, published. A great deal of empirical knowledge has developed through professional experience; this must be documented and disseminated to inform continued efforts.

Finally, research on the conservation of decorated surfaces on earth need not all be related to treatment. Exposure of decorated surfaces (especially excavated walls) to the elements is of great concern, and this raises the issue of the need for shelters and other preventive measures. This area is little addressed in the literature relating to decorated surfaces, and it warrants further investigation. The trends toward an understanding of original materials and techniques and toward more accurate assessments of deterioration mechanisms are encouraging. This research should be continued and expanded, in order to further a thorough understanding of the complex material conservation issues of plasters and painted surfaces.

The complexity of the architectural system, as well as the integral link between the surface and the architectural system, cannot be overemphasized. With a more comprehensive understanding of original materials, techniques, and architectural systems of decorated surfaces on earth, appropriate conservation measures can be taken, and a holistic approach to their long-term preservation can be developed.

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Wall-Inhabiting Organisms and Their Control in Earthen Structures

By Brian V. Ridout

Earthen and other masonry structures differ from timber in that, though they may provide a habitat for insects and other animals, they do not form a food source unless they also contain organic materials. Many creatures and plants that invade earth walls are likely to treat the wall as just another earth cliff or bank if the material is soft enough to colonize, and any protective render is damaged or missing. Most of the damage will be caused by primary colonizers, which actively grow or burrow into the wall material; secondary colonizers, which live in the holes or modified earth, may exacerbate the damage by their activities. A wide range of potential colonizing organisms may therefore cause damage to earth buildings. Reed and colleagues (Reed et al. 1979) and Chiari (1985) both discuss the problems caused by tree roots. Pearce (1997) notes that termites can cause significant problems in earthen walls. Matero and colleagues (Matero et al. 2000) reported that birds, rodents, insects, and other arthropods were enlarging cracks attributable to other causes, by their activities at Casa Grande. This was discernible from guano, spiderwebs, debris, and burrows. Ziegert (2000) records rats, mice, and spider infestation as causes of damage in German cob buildings—particularly mice, whose tunnels produced enormous cross section weakening in wet zones. Bowman (2000) adds mason bees in New Zealand to the list.

The following discussion concerns the primary colonizers noted in the preceding paragraph. Secondary colonizers—e.g., birds and spiders—have not been included because their activities may presumably be curtailed by filling cavities.

Tree and Shrub Roots

Subsidence and Heave of Foundations

If a building is constructed on clay soils, then seasonal tree root activity may exacerbate the natural seasonal cycle of clay dehydration and rehydration underneath the walls. This may ultimately damage the building. The tree will remove water from the clay during the growing season, and the soil will then rehydrate when the tree growth ceases. Kozlowski (1982) reviewed the suction pressure achieved by plants and trees. He found that the peak suction on the soil achieved by tree roots was typically about 1500 kPa. Biddle (1998) stated that the load stress on the soil exerted by the foundations of a low-rise building was generally about 100 kPa, which was far less than the effect of root suction, so that movement of the foundations could occur.

Biddle (1998) also stated that the recovery of the soil from dehydration was incomplete beneath the walls, so that each annual cycle of water movement leads to an accumulating water deficit, which could ultimately result in subsidence. If a building had been constructed on soil where a nearby tree had caused a persistent water deficit and the tree was removed, or if barriers (or severing) impaired the suction effect of the roots, then the soil would start to rehydrate and swell. This could cause the foundations to rise, resulting in heave. Williams and Pidgeon (1983) discuss how the removal of vegetation causes heave and damage to buildings on the highveld of South Africa. The science of swelling in soils and earthen materials is fully discussed by Nelson and Miller (1992).

Reynolds and Alder (1980) attempted to rank tree species according to the damage their roots might cause to buildings. Their ranking was based on a questionnaire sent to fifty professionals who were asked to give a subjective score based on experience for (among other things) the risk of damage associated with seventeen tree species. Cutler and Richardson (1981; 1989) also conducted a large survey, and produced a species ranking based on the radial spread of roots that had caused, or were associated with, damage. Biddle (1981) advocated a classification based on "water demand," while McCombie (1993) used a tree height/distance to damage ratio. Ward (1947; 1953) and Biddle (1979) in the United Kingdom and Hammer and Thompson (1966) in the United States produced earlier ranks. Biddle (1998) concludes that there is considerable overlap between species, no matter how they are ranked, and that there is no evidence that rows of trees will have an enhanced effect compared to single trees. The influence of trees grown in proximity will overlap with each other rather than be cumulative.

Direct Damage to Walls

Chiari (1985) states that a few visible plant leaves on the surface of an adobe structure can be supported by meters of large roots, which cause cracking in their search for water. Zwieniecki and Newton (1995) found that *Arbutus* roots could grow through fissures as thin as 100 µm in rocks, while pine, which was less well adapted, required the fissure to be greater than 0.5 mm. These, even for pine, are very small cracks and crevices. Misra, Dexter, and Alston (1986) measured root pressure exerted by different plant seedlings and obtained a mean axial pressure of 1032 kPa and a mean radial pressure of 866 kPa. There was, however, considerable variation, and the results were obtained from the primary growth of crop plants, rather than of trees. Nevertheless, Biddle (1998) believed that they indicated the order of pressure to be expected, and that when they were considered in conjunction with the potentially large surface area of secondary roots (perhaps 20 cm or more), they showed the potential risk from root damage. The forces exerted could be massive, particularly around the bases of trees growing out of structures. Almeida, Mouga, and Barracosa (1994) investigated damage caused to buildings by the root systems of *Ailanthus altissima* in Portugal and found that the damage could be severe.

Secondary roots also have the ability to deform around any object that impedes their growth. Materechera, Dexter, and Alston (1991), working with seedlings, found that a compaction that caused a 94% reduction in root elongation resulted in a 41% radial expansion for monocotyledon plants and an 87% radial expansion for dicotyledon species tested. Substantial radial growth can also occur as callus formation, following root damage.

Damage to Drains

Roots may travel along the unconsolidated backfill of drains, and fine roots may enter any cracks that are allowing water leakage. Fine roots will then proliferate in the drain, causing blockages and possibly enlarging the original crack. Cutler and Richardson (1989) indicate the tree species most commonly implicated in the United Kingdom. Cardozo (1981) discusses the damage caused by the roots of introduced *Ficus* species in southern Florida.

Occasionally roots may cause direct damage by growing around clay pipes, and Mattheck, Lonsdale, and Breloer (1994) discuss the mechanical principles involved.

Avoiding Root Damage

Damage may be prevented by not planting large trees in close proximity to buildings, and Gasson and Cutler (1998) showed how sensible use of available data can avoid damage. British Standard 5837 (British Standards Institution 1991), Biddle (1997), and Coombes (1985) all provided guidance in the United Kingdom. Balder (1998) gave an introduction to the subject in Germany.

Edwards, Rowe, and Trought (1999) described the control of tree growth by planting in geotextile fabric bags in New Zealand, and Moffat, Bending, and Dobson (1998) tested mineral and synthetic barriers with variable success in the United Kingdom.

Biddle (1998) discussed precautions against future damage when trees and buildings are already in close proximity. He suggested removing paths or paving slabs close to the base of the tree and severing the offending root in cases in which this would not destabilize the tree. Roots should be cut as far from the tree as possible, and the mass of small roots, which regenerate from the edges of the cut, will not cause a problem. He suggested that root severance should not cause instability, provided that the cut be made at a distance from the center of the tree that is greater than the tree circumference.

National Joint Utilities Group publication no. 10 suggests that flexible plastic drainage systems be used in the vicinity of trees (National Joint Utilities Group 1995).

Control with Herbicides

Biddle (1998) stated that the most effective herbicide for stump treatment is ammonium sulphamate, used either as a 40% solution or as crystals applied to the cut surface. He also mentioned 2,4,5,-T, 2,4-D (ester) and a triclopyr, dicamba, 2,4-D ester mixture as useful alternatives. The ester should be dissolved as 1 part in 40 parts of diesel or other light oil. Several other authors confirm the efficacy of these herbicides. Hamilton and McHenry (1982), for example, found that ammonium sulphamate, 2,4,5-T, 2,4-D, and glyphosate would prevent the sprouting of *Eucalyptus globulus* stumps, while Tabbush and Williamson (1987) showed that ammonium sulphamate, glyphosate, and trichlopyr would control the regrowth of *Rhododendron* in the United Kingdom. Marrs (1985) found that 2,4,5-T, ammonium sulphamate, glyphosate, hexazinone, and trichlopyr were all equally effective on birch stumps.

Jager and Oosterbaan (1979) found that while a saturated solution of ammonium sulphamate controlled stump regrowth, the best treatment for stems that he tested was glyphosate. Willoughby (1999) achieved similar results, when he found that imazapyr and trichlopyr provided adequate suppression of growth from ash, sycamore, and birch stumps but that glyphosate, which was ineffective when applied to the stumps, was very effective against regrowth shoots. The work of other authors also suggests that the best treatment for stumps is not necessarily the best for shoots and branches. Woodall (1982) tested eight herbicides against Brazilian pepper (*Schinus terebinthifolius*) and the tree *Melaleuca quinquenervia*, two exotic species that had become widely established in Florida. He found that bromacil and hexazinone were both effective, while ammonium sulphamate and glyphosate were not particularly useful. Popay, Rolston, and Edmonds (1985) controlled gorse bushes (*Ulex europaeus*) with metsulfon-methyl and glyphosate in New Zealand but had little success with ammonium sulphamate. Tripathi, Verma, and Sharma (1992) found that glyphosate, with or without oxadiazon or fluroxypyr, was effective against *Lantana camara* in India, and that the results from ammonium sulphamate were encouraging. These results all suggest that while ammonium sulphamate is useful for treating stumps and glyphosate (for example) is useful for treating shoots, suitability will also depend on the species of plant present, and this may necessitate field testing a range of herbicides.

Glyphosate, a systemic herbicide, will be carried through the root system and inhibit suckering. Suckering may also be suppressed by ringing the bark of the tree twelve months before the tree is felled, so that the roots are deprived of food reserves (Biddle 1998). These may be important considerations when dealing with tree or shrub damage to earth buildings. Some herbicides that are applied to stumps encourage colonization by decay fungi, and Rayner (1977a; 1977b) found that ammonium sulphamate strongly encouraged the growth of *Phlebia merismoides*. This potential may cause difficulties in arboriculture because some of the fungi encouraged may be important forest pests (Nelson, Pearce, and Malajczuk 1995), but the rapid decay of roots in walls may assist repairs and assist the exclusion of other pest organisms.

Roots in pipes may be killed with herbicides, which will not affect the tree. Groninger, Zedaker, and Seiler (1997) tested a range of herbicides and found that glufosinate was the most effective, although there was some damage to the plant tested.

Ferns and Bracken

Bracken and ferns can be vigorous colonizers with destructive rhizome systems. Rees and Mills (1999) state that both glyphosate and asulam will kill them, but asulam is reasonably specific. This should reduce damage to nontarget species.

Termites

About twenty-two hundred species of termites have been recognized worldwide, but only a few of these cause damage to crops or buildings, and only about fifty species have become serious pests. Termites reportedly caused damage to earthen buildings by tunnelling up the walls to reach roof timbers, and may be a significant problem where timber or bamboo poles have been incorporated into the construction (Pearce 1997). The modified soil produced by their activities may also improve the environment for other colonizing organisms (see the section on mason bees below). The scientific literature is vast, and the following provides an overview of a range of control methods that might be incorporated into a pest management program.

Termites are colonial insects related to cockroaches. They may be grouped into four categories based on their habits and moisture content requirements:

1. Harvester termites feed on grass and plant litter and rarely attack timber in buildings.
2. Damp wood termites live in old tree stumps, rotting logs, and pieces of buried timber. They rely on a considerable source of damp to survive. Once established, they can attack sound wood in the structure of buildings, but pest species are mostly restricted to the northwestern United States.
3. Dry wood termites live entirely within dry wood, and unlike the other groups, they are less dependent on an external source of moisture. They are able to survive above ground, and do not require access to the soil. This ability should make them major pests, but most only

occur in small colonies and are usually relatively easy to control.

4. Subterranean termites build their nests in the soil or on trunks of trees and rely principally on the soil for a source of moisture. Covered shelter tubes may be constructed from soil and saliva to protect the insects from desiccation when they forage. Some subterranean termites, notably *Coptotermes formosanus,* have the ability to exploit extraneous water sources—for example, leaking pipes. The subterranean termite group provides most of the major pest species in buildings around the world. Some species have been transported extensively by human activities. *C. formosanus*, for example, is a termite that originated in the Far East but has become a major pest in the United States.

Termite Treatments

It has become customary to differentiate between dry wood termite treatments, which may include building fumigation or localized treatments, and subterranean termite treatments, which include wall treatment and protection from invasion through the soil. It is worth remembering, however, that extensive treatment methods have mostly been developed to control some very aggressive species of termites in the United States and Australia. Methods that might have little impact on a massive infestation by *Coptotermes formosanus* in the United States may prove more effective against small and localized colonies of *Amitermes* species in the coral-rock walled buildings of Bahrain, for example. It will usually be worth identifying the species of termite involved and finding any information on its normal colony size and behavior.

A further problem is that new and effective antitermite formulations may not be registered for use or may be too expensive to use in some countries. I have tried to make this review as wide as possible by including a variety of methods that may be applicable where more exotic solutions are not available.

Fumigation

Dry wood termite control frequently includes the fumigation of whole structures with toxic gases. These gases are extremely hazardous, and they must only be used by fully trained technicians. Two gases, methyl bromide and sulphuryl fluoride, are currently used (Lewis and Haverty 1996), but there is now widespread concern that methyl bromide has an adverse effect on the ozone layer, and sulphuryl fluoride is considered to be the more acceptable alternative (Chambers and Millard 1995). The efficacy of both gases can be enhanced synergistically when mixed with carbon dioxide (Scheffrahn, Wheeler, and Su 1995). Either the gases are used in enclosed spaces or the buildings are covered with gasproof tarpaulins.

Termiticides

Organochlorine insecticides were the favored control method during the middle decades of the twentieth century, and these might give over thirty years protection to a building. Unfortunately, organochlorine insecticides also accumulated within the environment, and their use has been banned in most countries. Organophosphorus compounds (e.g., chlorpyrifos) and artificial pyrethroids (e.g., permethrin) have now largely replaced them, but they are not as persistent in the soil. Soil persistence is important because orthodox methods for controlling subterranean termites require the treatment of the soil around and, where possible, under a building to inhibit reinfestation. Retreatments, if control methods fail, may be prohibitively expensive in many countries (Edwards and Mill 1986).

A variety of organic termiticides have now been tested (e.g., Raetano, Wilcken, and Crocomo 1997; Scheffrahn and Thoms 1999; and Tan et al. 2000) and found to be more or less successful. Some of these were not specifically developed for the control of termites. Scheffrahn and Thoms (1999), for example, discuss the use of a fermented soil microorganism. This product was developed for agricultural use.

Inorganic salts seem to have been more problematic (e.g., Moein and Farrag 1997; Scheffrahn, Su, and Busey 1997), which is unfortunate because they are more likely to be available and affordable in many countries. These salts are generally used to control dry wood termites. Boron compounds, for example, when used for spray treatments, particularly disodium octaborate tetrahydrate, are considered to be effective by some authors (e.g., Jones 1991; Moore 1993) and less so by others (e.g., Scheffrahn and Thoms 1999). Boron compounds are also very water soluble and cannot be used for ground treatments.

A new class of biocides, the chloronicotinyl insecticides, has recently been developed (Elbert et al. 1991; Elbert, Nauen, and Leicht 1998). These were synthesized as agrochemicals, but two products containing imidacloprid have now been marketed as nonrepellent termiticides. Imidacloprid apparently acts as a nerve poison and, because it is nonrepellent and slow acting, a zone is created into which the termites may forage. Those that enter will slowly die. This mode of action differs from that of other termiticides, in which the chemical formulation produces a toxic repellent barrier.

Soil Treatments

The treatment of soil with termiticides in order to form a barrier between the termites and the structure (trenching or irrigation) has been a routine component of termite treatment since the 1940s. A standard for acceptable performance is that the insecticide used should prevent termites from penetrating 90% of the barrier for at least five years (Kard 1996). All of the commercially available organophosphate and pyrethroid soil termiticides have undergone vigorous simulated field testing and have been shown to be acceptably effective under the test conditions (Su and Scheffrahn 1990a; Kard 1996).

Persistence of the termiticide is, however, also dependent on the environment. Organophosphorus compounds may be less durable in tropical regions than they are in temperate ones (Pearce 1997), and chlorpyrifos, for example, was found to weather rapidly in the soil in Thailand (Sornnuwat et al. 1996). Part of the latter problem may be that fungi break down the insecticide, and the efficacy of chlorpyrifos was improved by mixing it with chlorothalonil, a fungicide (Laks and Pruner 1995; Creffield and Chew 1995). Nevertheless, chlorpyrifos may also bind to clay soils so that its efficacy is diminished (Pearce 1997), and the choice of termiticide in any particular area must clearly depend on a variety of considerations. More information on the relationships between termiticides and soil types may be found in a work by Gold and colleagues (Gold et al. 1996).

Irrigation and Spray Treatments

Orthodox termite treatments in buildings with solid walls usually include the drilling and irrigating of walls with the termiticide. This may seem to be essential with earth buildings, where termites are using the interiors of the walls as nesting sites or highways, but in some situations large numbers of irrigation holes, and large quantities of fluid, may destabilize the structure or cause surface damage through salt migration. If the wall interior is loose rubble or unbonded stonework, then it may be impossible without using a foam (see the section on foams below) to achieve an effective distribution of the insecticide and thus to treat any concealed timbers. This problem may perhaps be reduced if imidacloprid is used, because the chemical is claimed to repel termites, and even an imperfect treatment may slowly diminish the foraging insect population by attrition.

Foams for Cavities and Rubble Construction

Many of the termiticides available may be formulated as foams, and these have been developed for treating cavities and dispersing termiticides under concrete (Thomas, Barlow, and Robinson 1993; Potter, Hardy, and Richardson 1991; Robinson 1994). The insecticide is mixed with a foaming agent and distributed with a foam-generating machine. The size of the cavity and the loading of required active ingredient will both influence the characteristics of the foam. Damp foams with small bubbles are reported by equipment suppliers to penetrate well around gravel. Some products (e.g., imidacloprid) can be made into foams with minimal water content, so that water damage to finishes is avoided, although operators have expressed doubts that dry foams will allow enough of the active ingredient to penetrate surfaces effectively in some situations. Foams may be useful for treating loosely constructed rubble/stone walls, where there are embedded leveling timbers or poles.

Baits

Baits are attractants containing slow-acting toxicants, which are dispersed around the colony by the insect's natural social behavior. These chemicals may be direct poisons (e.g., Jones 1991), or they may inhibit some developmental process such as molting or cuticle hardening (Su and Scheffrahn 1990b). Their potential advantages as a control method, from an environmental point of view, are that only very small quantities of chemical are used, and that these chemicals are targeted at the pest insect (Su 1994b). They are particularly useful in situations where normal chemical methods are inappropriate. These situations might include access difficulties, the close proximity of groundwater, or the avoidance of damage to a historic structure or finish.

Some baits are seen as a method of termite control rather than of eradication, and they are often used in conjunction with chemical barrier treatments. Bait stations are frequently marketed as a preventative measure to provide an early warning of a termite attack.

Baiting is a slow process because there may be a significant delay before the termites find the bait station, and control may take many months to achieve. This means that the bait stations will have to be regularly inspected so that baits can be added or replenished as necessary. Regular monitoring may have cost implications that could make the process more expensive than chemical barrier treatments. Improvements in efficacy have been made by modifying commercial bait stations (Grace et al. 1996) and adding attractants (French 1991). Improving the attractiveness of the bait material may simply be achieved by making it damp (Delaplane and La Fage 1989), utilizing decayed wood (Esenther and Beal 1979), or adding a feeding stimulant such as urea (Henderson, Kirby, and Chen 1994).

Many baits have been tested with varying levels of success—see, for example, Pawson and Gold (1996), Forschler (1996), Henderson and Forschler (1997), and Madden (1999). The most successful bait at the present time, as judged by the number of technical papers supporting it, would seem to be hexaflumuron. The efficacy of this chemical has been well documented. Examples would include the control of *Coptotermes formosanus* and *Reticulitermes* spp. in the United States (Su 1994a; Rust et al. 1998; Getty et al. 1999); *Reticulitermes* spp. in Europe (Clement et al. 1996; Ferrari and Marini 1999); and *Coptotermes acinaciformis* in Australia (Peters and Fitzgerald 1999). Forschler and Ryder (1996) report on the baiting of four characterized colonies of *Coptotermes formosanus*, each containing an average of forty-three thousand termites, and covering a foraging area of 16 m^2. Three months after baiting commenced, activity in three of these colonies was undetectable.

Hexaflumuron is a chitin synthesis inhibitor and is used as the active ingredient in the first commercially available baiting system, which was introduced onto the market in the United States in May 1995 (Su and Scheffrahn 1996). A second and similar active ingredient, diflubenzuron, is now being used by a different company. These baits are only available as part of a commercial service, and the service is unobtainable or too expensive in many countries where there are earthen buildings in need of conservation. A third growth regulator, triflumuron, has recently been registered for use as an antitermite dust in Australia and may be useful either for topical application or as a bait. This compound was studied by Madden (1999). All of these active ingredients affect cuticle hardening, so the termites die when they molt. Other growth regulating chemicals, including fenoxycarb, methoprene, and hydroprene, increase the numbers of soldiers, presoldiers, or nonfunctional intercasts produced by a colony (Haverty and Howard 1979; Su, Tamashiro, and Haverty 1985; Pearce 1997). The extra soldiers and intercasts all need to be fed by the workers, and theoretically the colony ultimately starves.

Other baits tested have included the slow-acting poisons sulfluramid and fipronil (Henderson and Forschler 1997). The first of these is available in the United States as a professional system and as a do-it-yourself system for homeowners. The manufacturers of the homeowners system have been required to state that it is for monitoring rather than for termite eradication.

The general method of using a bait is to attract the termites to a box or tube containing an attractive food material, which may be nondurable wood or cardboard. The bait station is either placed in the ground or is set to intercept termite foraging. The mode of use will affect the design of the trap. Once termites begin to feed at the station, they are removed and treated, or transferred to a new bait container where the same food material now contains the toxic ingredient (Kletch 1996). Bait containers are replaced in the ground or in buildings, and the treated termites recruit others from the colony to the bait. Ballard (1999) has incorporated baits into an integrated pest management programme (IPM).

Grace, Yamamoto, and Tamashiro (1992) found that disodium octaborate tetrahydrate, impregnated into timber as a solution of strength 0.85%–3.0%, was toxic to termites and would suppress feeding but not stop it. Borate-impregnated rods have been used as baits and may be useful in some situations. Both borates (e.g., Forschler 1996) and fluorosilicates (Pearce 1997) have been used in low-technology baiting systems, but their main mode of action may be to poison the protozoa (microorganisms) that break down wood in the guts of the lower termites. The higher termites (Termitidae) make their own enzymes to break down wood, and their guts contain very few protozoa (Edwards and Mill 1986). It is possible that these baits may prove to be less effective against the Termitidae.

Criteria used to assess bait programs are discussed in Grace and colleagues (Grace et al. 1996), Su and Scheffrahn (1996), and Thorne and Forschler (2000).

Control with Pathogenic Fungi

Suzuki (1996) screened seventeen mold species for potential termite control. Three species, *Paecilomyces fumosoroseus, Metarhizium anisopliae, and Beauveria bassiana,* exhibited the best control. Delate, Grace, and Tome (1995) tested *M. anisopliae* and *B. bassiana*. They found that the termites did not avoid filter paper discs inoculated with the fungi, and that both caused rapid termite mortality. *Metarhizium* is now being evaluated for termite control in Australia (Staples and Milner 1996) and is marketed in the United States (Quarles 1999). Boucias and colleagues (Boucias et al. 1996) found a good synergistic effect with a combined treatment using imidacloprid and *Beauveria bassiana*. The insecticide weakened the termites and increased their susceptibility to the fungus.

Field tests using these fungi, particularly as baits, have shown mixed results. Possible problems are avoidance of the fungus spores and the removal and burial of infected individuals by other members of the colony (Rath 2000).

Heat and Cold Treatments

Rust and Reierson (1998) showed that the upper temperature tolerance level for dry wood termites was 49°C, and for subterranean termites it was 44°C. This supports a study by Woodrow and Grace (1977), who showed that termites would die if subjected to temperatures of 55°C for five minutes or 49°C for thirty minutes. Heat treatments may be practical in some situations, but they would have to be carefully monitored to ensure that adequate temperatures were maintained. Lewis and Haverty (1996) found that "heat sinks," for example, wood on concrete, might make some structures difficult to treat. The same authors also found that heating with microwaves could be useful.

Rust and Reierson (1998) showed that temperatures that were less than –20°C would kill termites, and Lewis and Haverty (1996) discussed gravity feeding liquid nitrogen into walls.

Termite Detection

If baits or targeted termiticides are to be used, then it is essential that active infestation be located, because baits do not normally contain attractants. There may be a considerable time lapse before the baits are located by the general foraging of the insects.

In 1929 Emerson and Simpson devised an apparatus for detecting termite activity using a microphone made from a telephone transmitter (Emerson and Simpson 1929). A major problem with this and other early devices was interference from extraneous sounds. Modern advances in transducers and amplifiers have allowed this problem to be largely overcome by the use of higher frequencies. Lemaster, Beall, and Lewis (1997) found that a frequency of 60 kHz maximized detection while minimizing background noise. Most of the acoustic detection devices that have been marketed detect vibrations caused by feeding, and not movement within a cavity. This means that the transducer has to be in intimate contact with the infested piece of wood, and use on earth walls containing timber would probably be limited. The detection of audible termite-generated sounds with sensitive microphones, or "electronic stethoscopes," remains difficult, because these sounds are easily masked by other ambient environmental noises (Scheffrahn et al. 1993).

Dogs or electronic devices may detect gases produced by subterranean termites. Lewis, Fouche, and Lemaster (1997) tested both methods and found that the dogs performed well, provided that enough termites were present in the sample. The electronic device did not demonstrate statistically significant detection ability. These authors state that "neither detection method was reliable with control samples [no termites] or with samples with a low number of termites" (p. 79).

Lewis and Haverty (1996) discussed other nondestructive search methods for entire walls, and these included microwaves and laser and infrared technology. Thermal imaging has been shown to detect termite colonies and might be useful for earth-walled buildings in some environments.

Small wooden stakes of various kinds, which are inserted into the ground, have been used to monitor termite colonies and to act as an early warning system for future infestations. Further details may be found in Ewart and colleagues (Ewart et al. 1992), French (1991), Su and Scheffrahn (1986), and Su (1994a).

Preventing Infestation

Many timber species are resistant to termite attack, and infestation should only be a problem if fungi change the density or chemistry of the wood (Pearce 1997). Fungi require water, and a good maintenance program, together with bait monitoring and the localized use of a combined fungicide and insecticide, may be more appropriate than extensive chemical treatments in many situations (Ridout 2000). Unfortunately, suitably durable timbers for repairs may now be impossibly expensive or unobtainable in many countries. One solution is to use pretreated lumber, and to use boron compounds (Myles 1994), copper naphthenate (Grace, Yamamoto, and Laks 1993), and copper, chromium, and arsenic formulations (Edwards and Mill 1986); all have their advocates.

Grace and Yates (1999) believe that prevention is better than cure, and they advocate, among topics already discussed here, the use of physical barriers. These are installed into the soil around the building in order to exclude foraging subterranean termites. Lenz and Runko (1994) found that fine stainless steel mesh placed under new buildings would provide an effective barrier. Grace and colleagues (Grace et al. 1996) found that the mesh would provide protection to structural timbers, but a field trial in Australia by Peters and Fitzgerald (1997) found that their termites would burrow 1.5 m under a stainless steel mesh sleeve to reach pine and eucalyptus poles.

A wide variety of granular materials have been suggested as trench infill barriers, and the idea is that the granules should be too big for the termites to move and too small for them to tunnel through (French 1993). Su and Scheffrahn (1992) demonstrated that a 20 cm deep layer of sand of grain size 2.0–2.8 mm would exclude *Coptotermes* and *Reticulitermes* spp. Ahmed and French (1996) found that finely graded crushed granite (marketed as Granitguard) excluded termites from a test building in Australia. Yates, Grace, and Reinhardt (2000) found that crushed basalt, marketed as a barrier in Hawaii, was an effective material, but that lack of understanding of installation requirements resulted in failures. They identified key problems and offered guidance. Lewis and colleagues (Lewis et al. 1996) observed that the monitoring of these barriers was essential, because the termites sometimes bridged them with foraging tubes. Removal of unnecessary timber around and within the building will remove reservoirs of infestation and reduce the food source available to the termites. This may help to limit the development of termite colonies (Haagsma et al. 1995).

Mason Bees

The names *mason bees* or *mortar bees* are used for species of solitary bees that nest in crevices or holes in masonry. Sometimes the terms are also used for bees that construct their nests from mud. Nests in walls generally consist of a single burrow or a series of branching burrows, each terminating in a chamber. Eggs are laid on pellets of pollen and nectar in the chambers.

Mason bees tend to exploit extant holes, but if the mortar or wall substance is soft, then the system of galleries or tunnels may be excavated by the females, and damage can sometimes be significant (Mourikis, Argyrious, and Tsourgianni 1988). Walker, McGregor, and Little (1996) mentioned severe infestation in a damp earthen wall where render had collapsed. The holes apparently allowed water into the wall that encouraged frost damage, and progressive decay resulted eventually in demolition.

Some species of bees in temperate climates overwinter in galleries and enlarge them or construct new ones the following spring. Populations can increase substantially over a few years. In the United Kingdom, damage usually occurs in south-facing walls.

Walker, McGregor, and Little (1996) and the Building Research Establishment (1996) both suggest repointing with an appropriate material that is not too strong for the general wall material yet hard enough to discourage the bees. Joints should be raked out squarely to a depth of at least 15 mm. The Building Research Establishment (1996) suggests that the work be undertaken in the late summer to avoid the bees and the frost.

The same authors suggest injecting the holes with insecticides and spray treatment with the same solution, if the work can only be undertaken when the bees are active. They suggest that an annual spray treatment during the spring may be necessary if the bees are burrowing into the actual building material rather than the joints, unless a render coat is acceptable. Pearson (1992) recommends discouraging them at the first signs of activity by hanging mesh over the wall. If this fails, then he suggests injecting the holes and spraying the walls every autumn.

Mourikis, Argyrious, and Tsourgianni (1988) state that they reduced the numbers of bees with light traps, but unfortunately no further details are given.

Rodents and Burrowing Animals

Rodent burrowing activity has a direct effect upon a wall, but it also modifies the environment for the organisms. Rodents, lizards, snakes, and many species of invertebrates may make use of burrows (Skinner and Smithers 1990), and the burrowing activity will loosen the compaction of the earth used for construction (Dickman 1999). The latter environmental change alone may make the environment more suitable for seed germination (Contreras and Gutiérrez 1991) or for root growth. Comparisons of soils from rodent mounds and undisturbed intermound areas have also shown a difference in organic content, water-holding capacity, and nutrient status (Hobbs and Hobbs 1987; Inouye et al. 1987; Huntly and Inouye 1988). Some, or all, of these effects may be produced by rodent activity in, or at least in the vicinity of, earthen walls and thus make the walls more accessible to a wide range of colonizing organisms. Many species of rodent hoard seed for later consumption (Reichman and

Price 1993), and some of these seeds may survive to germinate and become established (Vander Wall 1990) because the environment within rodent burrows is generally quite humid (Reichman and Smith 1990).

Substrate moisture content may be of considerable importance to burrowing animals, and some may not be able to excavate if the soil is dry and hard (Reichman and Smith 1990).

Rodent Control

Lethal chemicals still play a major role in developed countries for the control of rodent pests. These compounds may be used as baits, liquids, dusts, or gases (Buckle 1994). Poisons fall into two main categories, acute and chronic. Frequently one or the other is chosen, but Pathak and Saxena (1997) achieved 100% control of rodent pests in Jaipur by using an acute and a chronic poison sequentially. A subacute category is sometimes mentioned, but this is ill defined (Buckle 1985).

Acute Poisons

These usually produce an onset of toxicosis within twenty-four hours. If the poison is supplied as a bait, then the animal has to eat an amount sufficient to kill it, without being repelled by the taste or only made sick so that it subsequently avoids the bait (Prakash 1988). The latter effect is of particular importance because many rodents only nibble lightly at an unfamiliar food until confidence is established (Barnett 1988). One advantage of acute poisons is that they tend to be fairly simple compounds and therefore inexpensive (Meehan 1984).

Chronic Poisons

Anticoagulant rodenticides developed in the United States from observations that feeding on spoiled clover hay caused hemorrhagic disease in cattle. The active ingredient was found to be dicoumarol (Link 1944), and a series of synthetic derivatives, including warfarin, were developed (Buckle 1994). Resistance of rats to warfarin was first reported from Scotland in 1958 (Boyle 1960), and this became a significant and worldwide problem that was only overcome with the development of "second-generation" anticoagulants (Hadler and Shadboldt 1975). Control of a rodent population is usually achieved by pulse baiting (Dubock 1984) in which small quantities of bait are used at weekly intervals. Baits may be formulated in cereals, pellets, or wax blocks.

Barriers and Traps

Physical control methods, which would include barriers, traps, rat drives, digging, and netting (Singleton et al. 1999), are the normal methods of rodent control in many developing countries. This may be because of cost or availability of rodenticides, or because some governments are becoming concerned about the misuse of chemicals (Singleton 1999).

Barriers have been constructed to protect fields of rice in the Philippines (Quick and Manaligod 1990) and could presumably be used in some circumstances for buildings. Meyer (1994) suggested the construction of a concrete curtain wall, about 100 mm thick and extending not less than 600 mm below ground, with the base turned out some 300 mm away from the building in the shape of an L. He also suggested that applying a horizontal band of smooth rendering, which could then be painted with two coats of high-gloss paint, could prevent rodents from climbing up vertical walls. A strip of smooth metal sheeting could be applied to wooden buildings. All bands should be about 20–30 cm wide and not less than 1 m above the base of the outside wall. Protective collars of aluminum foil or rigid plastic have been used to protect trees (Myllmaki 1987), and these may be useful in other situations. Smith (1994) provides the following guidance for rodent-proofing buildings:

- Materials must be proof against gnawing, e.g., brick, concrete blocks, sheet metal, or fine-mesh metal.
- Apertures should be 6 mm maximum.
- Climbing guards must be sufficiently high up drainpipes, etc., to prevent jumping beyond, and wide enough to prevent them climbing around.
- Drain traps should be used, to prevent access through drains and sewers.
- Doors must be kept closed and free of debris.

Wilkins (1982) found that rodents were unwilling to cross open areas such as roads, and the avoidance of shelter around buildings might be a useful preventative measure. Good hygiene within the building is also essential for rodent control (Meyer 1994).

Many types of traps are available for catching small rodents, and these may be either single or multiple catch; they may either catch the animal alive or kill it (Kaukeinen 1994). Greaves (1982) believes that effective control is only possible if a large number of traps are used, and he recommends two or three times the estimated number of rodents present. It would seem that traps alone would only be of value if there were a very small population of rodents. They may, however, be of value for monitoring as part of an integrated pest management scheme that uses a range of control measures.

Smith (1994, 109) states that the "primary aim of pest management should be to reduce damage, rather than to kill the pest," and many problems with animals that excavate into earth buildings can probably be controlled by repairing the damage and by frequent maintenance. Smith (1994) also discusses a variety of additional control methods, including electric fences and diversion feeding. The use of fencing, trapping, or shooting has been recommended for larger mammals (Dunwell and Trout 1999).

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