Consolidation Studies

ABSTRACT

The Getty Conservation Institute, in association with the Museum of New Mexico State Monuments, began a field-test program early in 1988 at Fort Selden State Monument in southern New Mexico. The purpose is to evaluate, using adobe test walls, various preservation materials and techniques. These include chemical consolidants (mainly diisocyanates, and silanes); techniques of application of consolidants (spraying, brushing, bulk infiltration), surface and depth treatments; drainage, shelter designs and materials, reburial techniques for archaeological sites, and some structural reinforcing materials and methods. Accelerated aging through water spray has been used on the walls and their condition has been monitored stereo-photographically. This paper presents the experimental design. Some preliminary results are given in subsequent papers in the present preprints.

KEYWORDS

Adobe, consolidation, site stabilization, site shelters, isocyanates, silanes, outdoor accelerated aging, stereophotographic monitoring.

THE GETTY ADOBE RESEARCH PROJECT AT FORT SELDEN. I. EXPERIMENTAL DESIGN FOR A TEST WALL PROJECT

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Introduction

At the end of 1986 a three month pilot research project was undertaken at the Getty Conservation Institute (GCI) laboratories into the use of various chemical consolidants and other protective measures for the conservation of historic and archaeological adobe. While adobe was the primary focus of this research, it was implicit that the findings could have application to other earthen structures as well, and to outdoor heritage sites in general. The report on this work [1] and subsequent research over a nine month period showed that there was sufficient promise in chemical consolidants to warrant their field testing. The consolidants that tested most satisfactorily against deterioration by water and salts were aliphatic diisocyanate prepolymers and commercially available alkoxy and alkylalkoxysilanes. Preliminary results have been published [2-5]. Physical measures of protection and reinforcement of adobe structures were also planned in a comprehensive program of field testing.

The present paper describes the research design and implementation of the continuing field testing at Fort Selden. Preliminary results of the field testing are given elsewhere in the present publication. After the first phase of research a collaborative program was established at Fort Selden State Monument, where the Museum of New Mexico State Monuments (MNMSM) had already established a test wall facility. By late 1987 the design of the experimental system had been completed and construction of the test walls was finished in February 1988. Integral aspects of the design of the field project were an accelerated weathering (water spray) system, and regular temperature, moisture, and stereophotographic monitoring. Treatment of the test walls was completed by the end of May 1988 and testing began August 1, 1988 with the start of spraying.

The Need for Adobe Preservation Research

A significant component of the world's architectural heritage is built of earth, and the problem of preservation and protection of earthen structures is one of world-wide concern. In the late 1960's an Iraqi-Italian Center for the Restoration and Preservation of Monuments, with the collaboration of ICOMOS and ICCROM, was set up to study the preservation of unbaked brick. Its brief was to:

"systematically undertake collection of data, chemical and physical analysis of the bricks, research into the causes, concomitant and otherwise, of their degradation and be able to suggest methods most suited to give lasting results" [6].

Four international meetings on adobe were organized under the auspices of ICOMOS (Yazd, Iran in 1970, 1976, Santa Fe, USA in 1977 and Ankara, Turkey in 1980). The recommendations of the United States ICOMOS - ICCROM Adobe Preservation Working Session in Santa Fe in 1977 [7] called for (among other things) research into:

- Surface and subsurface drainage of mud-brick structures.
- Chemical surface treatment and consolidation.
- Injection and grouting techniques for consolidation or weather-proofing.
- Structural stabilization and reinforcement materials and methods.

In addition the ICOM-ICOMOS mudbrick symposium in Ankara in 1980 [8] recommended:

- Design studies be made of low-cost shelters that afford protection against direct erosion by rain or melting snow, provide thermal insulation but avoid the "greenhouse effect" and preferably be permeable to water vapor; and that shelter design concepts be tested in the field.
- Pilot field projects be undertaken to test conservation systems on entire structures.

In his introduction to the 1980 Ankara symposium on mudbrick preservation Torraca [9] noted the following points and problems for which a satisfactory solution was not yet in sight:

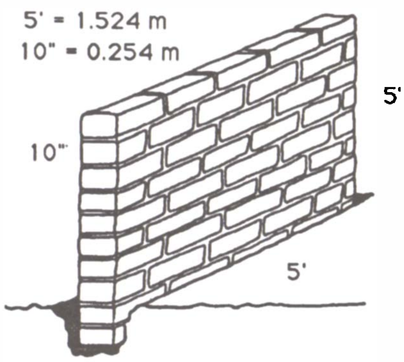

Figure 2. Schematic diagram with depth of test wall foundations and typical test wall dimensions.

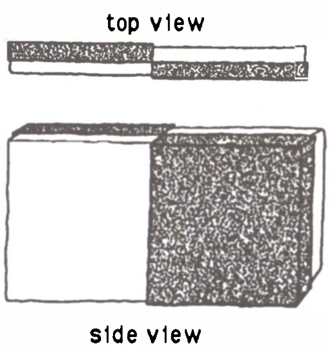

Figure 3. Schematic diagram of diagonal plastering of opposite sides of adobe test walls. The wall shown for the side view is one of the half walls.

•The long-term reliability and efficacy of partial protection methods including chemical treatment, capping and coating were questioned on the basis of recent experience and the high cost of these processes.

•Shelters open on the sides are effective at intercepting rain (and so stop this most damaging factor), but they allow a slow process of crust formation to occur. This is probably due to humidity/temperature cycles which are intolerable for decorated surfaces.

•There is a trend to either complete physical protection (by enclosures or reburial) or reliable maintenance routines.

Clifton [10] has reviewed the status, to 1976, of adobe preservation technology. He concluded that the successful preservation of adobe depends on effective protection of structures from the elements, especially water. He emphasized the need for analysis of the unique set of deteriorative factors operating at each different structure on site; the selection of preservation materials and standardized test methods; and pointed out the unlikelihood of the existence of a single universal preservation material process. Finally, he emphasized the importance of documenting and monitoring preservation processes that have been implemented. The research design presented here and the materials chosen for field testing address most of the concerns listed above - though not necessarily comprehensively in each case.

Deterioration of Adobe and Preservation Approaches

Much has been written about the effects of environmental factors, particularly water, on earthen structures. These include weathering by rain and snow, capillary rise of moisture into structures, migration of soluble salts, moisture-induced swelling and shrinking cycles as the material is melted, dries and so on. These and other deteriorative factors such as temperature, freeze-thaw cycles, wind erosion, and biological and human factors have been discussed [10, 11].

Likewise, the pros and cons of various treatment options involving chemical and polymer systems have been debated. In particular the question of penetration by surface applications and permeability of the treated surface has been one of concern [12]. For these reasons a variety of treatments, including spray, brushing and bulk-infiltration using a gravity-fed reservoir system were included in the design.

Test Wall Construction

After completion of an archaeological survey of the area for the test walls at Fort Selden, and final approval of the test wall design, construction began in December 1987. Figure 1 shows the plan view of the test wall site along with some individual wall treatment / experimental conditions. The standard test wall was 1.52 x 1.52 m by approximately 0.25 m thick (5 x 5 feet x 10 inches) constructed from nominal sized bricks 35.5 x 25.4 x 10 cm (14 x 10 x 4 inches). Wall foundations were 20.3 cm (8 inches), or two adobe bricks into undisturbed earth (Fig. 2). Diagonally opposite sides of the walls were mud-plastered (Fig. 3).

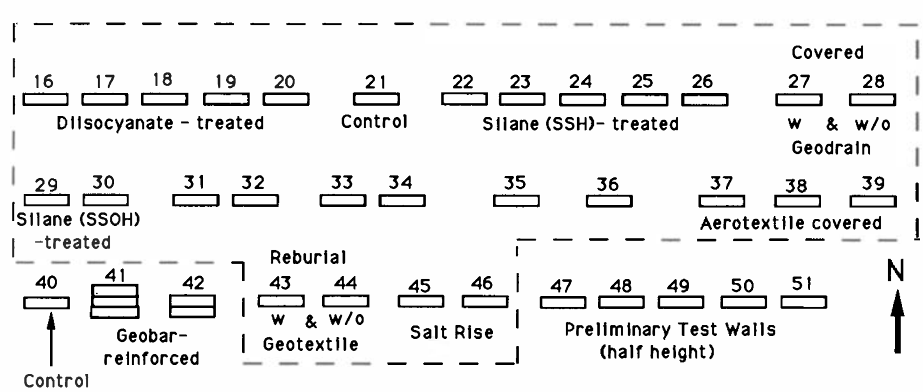

Figure 1. Map view of test walls at Ft. Selden, N.M. showing wall number and type of treatment / experiment. Area enclosed by dashed line represents walls subjected to accelerated (water spray) weathering.

Figure 4. Photograph showing chemical consolidant being applied to adobe test wall by spraying.

Chemical Treatments

Chemical preservation is the application of a substance, usually a polymer in solution or a monomer which converts in situ into a polymer, and confers its properties of durability, strength (consolidation), weather resistance and so on.

From the extensive literature on the preservation of adobe by chemical treatment, from the evidence of the present research, it has been possible to define the requirements of an hypothetical "ideal" system which will minimally alter the inherent properties and appearance, yet confer durability. These have been reported [3].

Figure 5. Photograph showing chemical consolidant being brushed onto adobe test wall.

Figure 6. Photograph showing adobe test wall being treated with chemical consolidant using bulk infiltration technique.

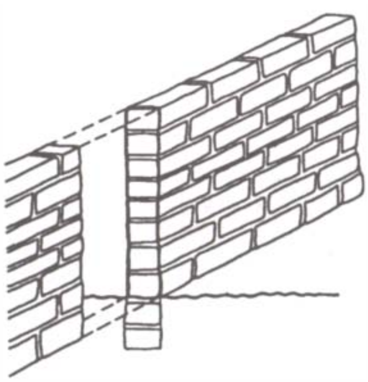

Figure 7. Schematic diagram of pattern of consolidation for walls treated by single surface coating.

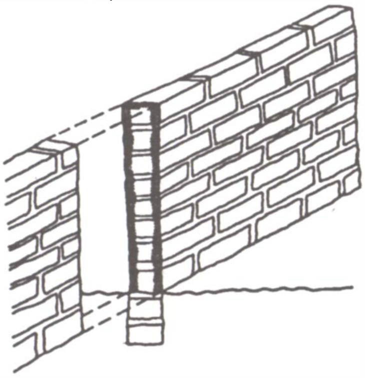

Figure 8. Schematic diagram of pattern of consolidation for walls using multiple surface coatings.

Consolidants - Application Techniques

Consolidant solutions were applied to the test walls by spray, brush and from reservoirs with infiltration tubes into the core of the wall (bulk infiltration) as shown in Figs. 4-6. Five basic patterns of consolidant application .were used. These are: surface coating (using minimal material); multiple surface coating (wet-on-wet) to achieve good depth of penetration; bulk infiltration to fully permeate the test wall; surface coating together with basal infiltration of the wall footings; and partial infiltration of the top and bottom of the wall and footings, with only light surface treatment on the vertical face. These patterns are depicted schematically in Figs. 7-11 which were chosen to provide as full a range of treatment responses to the perceived patterns of erosion of adobe walls.

Control Walls

A series of control walls is incorporated into the experimental design. Thus, there is a master control wall (#40, used also for thermal monitoring) that is not treated, nor sprayed, but exposed only to natural weathering; a control wall not treated but sprayed (#21) to monitor the effect of spraying on natural adobe. For the geodrain and simulated reburial test walls there are control walls without drains and without geotextile (#27 and #44, respectively).

In general, each wall can be referenced to one (or more) other wall(s) in which only one variable has changed, for example, the isocyanate (DN3390) - treated series (#16-20) is compared directly with the silane (Conservare SSH) - treated series (#22-26), and each series can be compared with the sprayed control (#21) and the master control wall (#40). Likewise, the effect of physical protection of adobe against spraying (simulating rain) by using knitted synthetic fabric ("aerotextile") as a shelter material can be judged by comparing the sprayed control wall (#21) with a sprayed, sheltered wall (#39).

Accelerated Weathering

It can take a long time for results from field testing under natural conditions to become apparent. To avoid such delay an accelerated weathering water-spray system at Fort Selden was used. The results of an artificial testing regime such as the present one are comparative only and are not intended to be absolute, nor will they necessarily relate in a quantifiable way to natural weathering. However, the results do allow certain valid conclusions to be drawn when judging one process against another and when suitable controls are included in the design.

Important criteria to be decided when initiating a spray regime are: frequency of spraying, time of day of spraying, volume of water per spray cycle, force of spray jet, uniformity and pattern of spray impinging on the wall. Also, local rainfall and meteorological conditions need to be recorded, as these obviously add to the weathering rate.

The initial spray program at Fort Selden proved to be too aggressive and after two months was stopped during a particularly wet summer. The initial spray program comprised two 15 minute cycles daily (at 0900 and 1600 hr). Each nozzle sprayed approximately 22 liters of water per cycle. Thus, the total water load per wall per two cycles daily was 88 liters, or over the two months of initial spraying approximately 1400 gallons. ·During this summer approximately 64 mm (25 inches) of rain also fell. Several walls (#30, 32, 46) collapsed during storms - presumably because of wind load on nearly saturated walls and footings.

Monitoring --- Photographic, Temperature and Moisture

A protocol for stereophotographic recording of the condition of the test walls has been developed. This comprises 6 x 6 cm format stereopairs taken at night with standardized lighting to avoid the variable effects of daylight . Approximately once monthly one side only (to minimize the cost) of each test wall is photographed. A single batch of film is used and standard processing of the negative is carried out. It is intended that quantitative information will be derived from the negatives by digitization and image processing. Fig. 12 shows a single contact print of one of a stereopair.

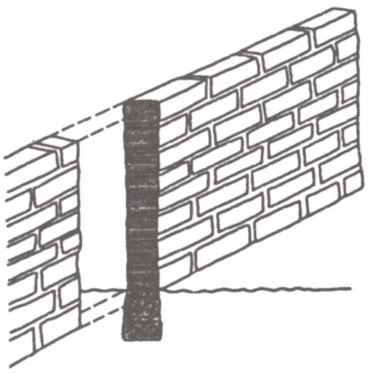

Figure 9. Schematic diagram of pattern of consolidation for walls treated by bulk infiltration.

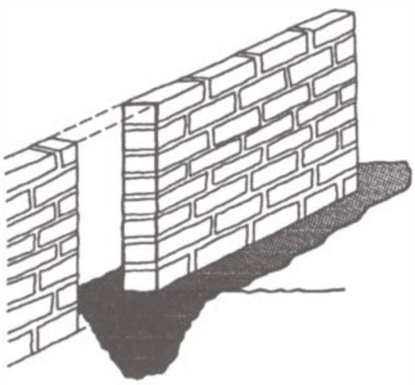

Figure 10. Schematic diagram of pattern of consolidation for walls treated by surface coating & basal infiltration.

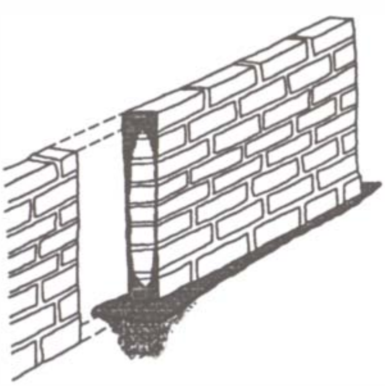

Figure 11. Schematic diagram of pattern of consolidation for walls treated by surface coating and partial infiltration at top and base.

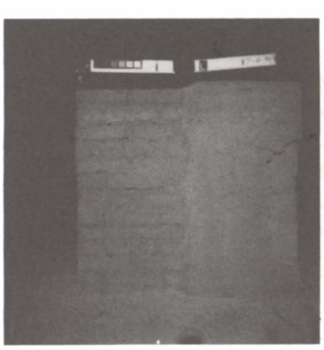

Figure 12. Contact print of one of a pair of stereophotographs taken of test wall #20 (DN3390-treated). Note cracking of outer plaster surface from accelerated (water spray) weathering.

Surface and interior temperatures of the master control wall (#40) are monitored for 24 hours at a time on a seasonal basis using thermocouples and a 16-channel data logger system. This system is shown in Fig. 13. Thermocouples are embedded on the surface and at depths of 2.5 cm and 12.5 cm on the east and west faces of the wall both on the adobe brick and the mud-plaster surfaces.

Moisture monitoring in selected walls (the control wall, geodrain walls, and others such as the basally infiltrated walls) is done using a calibrated resistivity meter and preset pins. Results so far are of doubtful value. Occasionally moisture determinations have been done by coring and use of a calcium carbide meter. Core holes are sealed afterward with silicone rubber plugs.

Protective Structural Experiments

As stated previously the resolutions of the 1980 Ankara conference on mudbrick [7] proposed lines of research on shelters and temporary low-cost protection. However, the design, construction, aesthetics, cost and long-term effects of shelters have not received much attention until recently. In the protection of adobe sites from the weather, shelters have an important role.

There are three important criteria that should be considered in research into shelter design and materials. These, in order of importance, are effectiveness, cost, and visual or aesthetic impact on the scene. Effectiveness should cover all the desirable requirements mentioned above for site protection; cost is obviously important, especially in remote or poor areas, and the aesthetic appeal is relevant where a site is on show to visitors. All shelters will intrude on the landscape to some extent, but a sensitive design will clearly find more acceptance that one at odds with the structure it is protecting. Adobe is especially demanding because of its earth color, rounded and weathered contours and the fact that often it can be overpowered by modern materials such as steel which lends itself to rectilinear design and construction.

A synthetic, knitted shadecloth (or "aerotextile"), originally developed for the horticultural industry, was chosen for evaluation as a shelter material. Fig. 14 shows the structure of the 70% shade density grade. Shelter designs usually try to totally protect easily weathered material like adobe. The basic premise in proposing this open-weave textile for testing was that in many cases a completely water-proof shelter may not be needed, particularly if the adobe site can be treated, as part of the site protection program, with a chemical preservative.

The advantage in testing this aerotextile for shelter use are:

•It breaks the force of rain and will prevent snow from accumulating on the structure.

•It has a wind attenuation factor of 60-70 percent (for the 70 percent density fabric, as shown in Fig. 15). It thus breaks the force of the wind, without any possibility of creating dangerous turbulence which is always a hazard with shelter roofs and walls that are solid. It will also cause wind-borne sand to be deposited if side screens are used.

•The textile is available in a range of "shade densities" of 40, 50, 70, 90 percent light reduction.

•It can be used to ameliorate thermal stress on fragile or heat-susceptible structures (e.g., east-facing walls) when an appropriate shade density is chosen.

•It will inhibit growth of vegetation on sites by cutting down light. In many ruins growth of weeds and robust plants causes great damage through invasive root systems. Thus it will also cut down on the need for expensive maintenance and herbicide treatment.

•It is inexpensive; has a 25-year guarantee in any outdoor situation (the polymer is UV-stabilized polyethylene) and is light in weight and easily transported. It could find application in remote areas and in third-world countries where relatively unskilled labor could be used in construction.

•Being light in weight, open-weave, and tear-proof it does not demand the use of massive (and costly) support structures but can be constructed on light tubular steel and wire framework. Methods of fixing the textile to free-standing frameworks are well established. In addition, conventional shelters of steel, bricks or concrete are normally supported by robust pillars, the installation of which pose a threat to a site both in the excavation of post holes and in the use of heavy machinery for the handling and erection of the structure.

•It allows circulation of air and thus avoids the stagnant microclimates characteristic of totally enclosed protective shelters.

•It is available in a variety of colors, beige, brown, black, green, white --- the beige probably being most suitable for an adobe site.

•If handled sensitively in shelter design it need not intrude unduly on the

Figure 13. Photograph of control wall (#40) with thermocouples hooked up to data logger for exterior surface and internal temperature monitoring.

Figure 14. Structure of aerotextile material with 70% shade density.

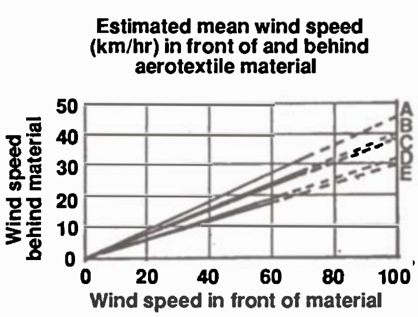

Figure 15. Graph showing effect that different density grades of aerotextile material has on mean wind speed. Curves A, B, C, D, E correspond to density grades of 40%, 40%, 50%, 70%, and 80%, respectively. Solid line represents measured wind speed, dashed line represents predicted wind speed. (Information provided by Technisearch, Melborne, Australia).

historic landscape of the site it is protecting.

There are apparent disadvantages in the use of this material:

- Being open-weave it is not water-proof.
- It is not fire-proof and is easily vandalized.
- It will tend to sag slightly between supports and cause drips at particular points. These will erode holes in adobe.

The main disadvantage of the textile, that of being non-waterproof, can probably be overcome by treatment of the material being protected with a chemical preservative; deep surface impregnation rather than bulk infiltration may be sufficient.

Technology transfer of existing materials - such as aerotextiles and geotextiles (as discussed in the next section) - from the horticultural and civil engineering fields respectively, to applications in adobe site-preservation research, indeed, heritage sites in general, has many clear benefits. The development work has been done and the materials are being marketed internationally and have proven acceptance and durability. Furthermore, they are often available in a range of grades which allows matching with site requirements. Thus, by comparison with steel-roofed constructions, material such as aerotextiles would appear to have great advantages in cost-effectiveness, ease of erection, and aesthetic acceptance with minimal intrusion on the historic site landscape. Two aerotextile shelter designs were used at Fort Selden and are shown in figure 16. These are an A-frame shelter (walls #38 & 39) and a puckered hexagonal ring structure (wall #37).

Ground-Water Control and Water-Proofing Foundations.

The problem of ground-water control has been reviewed thru 1979 by Clifton and Davis [13]. These authors also discuss the possibility of water-proofing foundations and underlying soil and conclude that the approach appears worthy of evaluation in field testing.

In general, ground-water control is best handled by installation of drainage systems. Trials are being carried out at Fort Selden on drains of advanced design. These are less intrusive of soil (and archaeological deposits) around the base of adobe structures than traditional gravel-filled drains (Fig. 17). Stripdrain and Cordrain are such drains. They consist of a non-woven polyolefin geotextile sheath, as a filter to prevent clogging, surrounding a dimpled plastic core (40 mm wide in the case of Stripdrain). This material is superior to conventional slotted agricultural drain-pipe on the following counts:

- It is more efficient as a filter in preventing blocking.
- It is able to intercept water flow in several subsoil layers and enables drainage of high volumes.
- It is tolerant to grade inconsistencies over long lengths.
- It can be installed in narrow trenches with minimal excavation of subsoil.
- It is stiff vertically and can bridge small variations in the trench base.
- It is flexible and can be bent around corners.

Reburial

Many authorities consider reburial of an excavated site - adobe as well as other categories of archaeological sites - as the only responsible measure when protection and preservation are not possible [14]. Adobe sites, in particular, deteriorate rapidly on exposure as previously stated [14]. Yet little work has been done on the effectiveness or otherwise of reburial as a preservation method. Soil disturbance on excavation increases permeability, and if the excavation material is used as backfill the percolation of water and access of air is increased. Thus, reburial may, in some instances, cause unwitting accelerated deterioration.

A common practice in reburial is to use a layer of clean sand as a marker in the event of future re-excavation. In remote areas sand is not always available and transport costs may be high. Sand is ineffective in covering and delineating vertical surfaces that are being reburied. These considerations have prompted consideration of the need for assessment of geotextiles as a reburial shroud for adobe (and other) structures. This fabric is available in different weights and is used as the external sheath in the geodrain systems already discussed. The fabric is permeable and will not create wet, anaerobic conditions around structures that plastic sheeting - which has been used on some sites - may cause. It will conform to the profile of a structure and provide physical protection on both burial and re-excavation.

Two walls (#43, 44) have been used for this experiment, in which half the wall was built below grade (see Fig. 18). The experimental wall was draped with Mirafi 140 NS geotextile and then buried until only the top of the wall showed. The control wall was was not draped but was similarly buried. Both walls have been water sprayed.

Figure 16. Photograph showing adobe test walls (#38, 39) protected by A-frame, aerotextile-covered shelters, and (#37) by hexagonal shaped 'puckered' shelter with aerotextile roof.

Figure 17. a) Close up of geodrain showing black plastic core and white geotextile fabric. Manufactured under the name Cordrain, by Nylex Corp., Australia. b) Photograph showing geodrains in place and being buried by author.

Structure Reinforcement

Damaged adobe sites may result from weathering or seismic activity. The effectiveness of synthetic internal reinforcing bars ('geobars') on test walls at Fort Selden is being assessed. The bar is a rigid, fiberglass rebar 12.5 mm in diameter, externally ribbed. It is non-rotting and non-corroding. Test wall configurations similar to that shown in Fig. 19 are being tested. Two methods of inserting the rods have been used. In both a 13 mm pilot hole is first drilled into the adobe wall. This is then filled with water and the resulting mud is extruded using a 50 mm auger bit (with extensions as necessary). The geobar is inserted and in one case the hole is filled with mud, in the other polyester resin was poured to fill the hole, thus giving a 50 mm diameter rigid rod. Two walls (#41, 42) were reinforced with the geobars; however wall #42 has collapsed leaving one geobar-reinforced wall for evaluation.

Conclusion

The Fort Selden field experiment was designed and set up as a large-scale outdoor laboratory experiment to assess certain treatments as a preliminary to real-site implementation. In order to achieve results within a reasonable time frame an accelerated weathering spray system was used. Results of two and a half years of combined natural and artificial weathering are appearing. It is expected that final comparative evaluation of the various measures implemented on the test walls will be possible by the end of 1991.

Acknowledgements

The author acknowledges with gratitude the contributions of his co-workers at the GCI, Dr. Charles Selwitz, Richard Coffman, & Dr. Frank Preusser. Special recognition is due James Druzik (GCI) and Thomas Caperton (MNMSM) who helped initiate the project. Michael Taylor (NPS formerly with MNMSM) who worked on site in May 1988 with the author and has been an active collaborator throughout. Frances Gale of Pro So Co also worked on site applying the Conservare H & OH consolidants generously donated by her company. Mobay Corporation has unstintingly supported the project through donations of diisocyanate prepolymers, and Mike Jakstis of Mobay has provided much useful guidance. Paul G. McHenry Jr. (designer of the test site) and his sons Bruce (construction) and Jamie (photomonitoring) have likewise been integral components. The Fort Selden staff, especially Jose Guzman and Elva Melendez have provided help whenever it has been needed. Thomas Moon developed the photodocumentation protocol.

Note: Technical specifications and plans for the construction of the test walls and the spray system are available from P. G. McHenry, Jr., 834 Griegos Rd. NW, Albuquerque, N.M. 87107.

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Figure 18. Photographs showing geotextile-covered and uncovered walls (#43, 44, respectively) a) prior to burial, and b) after burial.

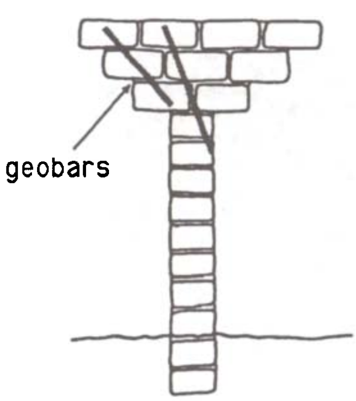

Figure 19. Schematic diagram of test walls containing structural reinforcing elements.

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THE GETTY ADOBE RESEARCH PROJECT AT FORT SELDEN II. A Study of the Interaction of Chemical Consolidants with Adobe and Adobe Constituents

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ABSTRACT

Treatment of adobe with hexamethylene diisocyanate-derived polymers and silanes increases compressive strength and consolidation, and enhances resistance to disaggregation by water. To better understand the modifications of the properties of natural adobe, the effects of treating individual components of adobe (clay, silt, and sand) with chemical consolidants were examined. Several different clays (Na- and Ca-montmorillonites and kaolin) were treated with isocyanate and silanes as were mixtures of clay and quartz sand, quartz sand alone, and adobe. X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM), grain size analysis, water sorption analysis, and compression testing were used to evaluate the effects of the chemicals on consolidation, modification of compressive strength, and resistance to disaggregation by water in clays, sand-clay mixtures, and adobe. The results of these evaluations indicate that the clay type plays a significant role in the properties of isocyanate- and silane-treated adobe.

KEYWORDS

Adobe, clays, compressive strength, consolidation, isocyanates, silanes, water repellency, x-ray diffraction analysis

TABLE 1: Evaluation of Compression Tests on Sand:Clay Plugs

Clay type (Letter refers to figures 1 and 2)	Mean Stress & (Std. Deviation) at Failure) in MPa	Mean Modulus & (Standard Deviation) in MPa
KGa-2 (A)	0.099 (0.027)	11.124 (4.305)
KGa-2 (B)	2.695 (0.380)	116.563 (35.335)
KGa-2 (C)	3.220 (0.918)	147.491 (64.594)
KGa-2 (D)	2.196 (0.180)	124.931 (42.099)
KGa-2 (E)	1.827 (0.200)	92.169 (15.699)
SAz-1 (A)	0.131 (0.037)	10.776 (5.418)
SAz-1 (B)	1.104 (0.212)	74.167 (19.838)
SAz-1 (C)	2.878 (0.308)	181.605 (68.047)
SAz-1 (D)	1.400 (0.226)	99.407 (27.434)
SAz-1 (E)	0.931 (0.140)	87.423 (25.340)
SWy-1 (A)	0.015 (0.003)	1.648 (0.819)
SWy-1 (B)	0.099 (0.041)	13.748 (8.042)
SWy-1 (C)	0.297 (0.297)	20.353 (3.791)
SWy-1 (D)	0.458 (0.059)	45.501 (10.837)
SWy-1 (E)	0.365 (0.027)	27.221 (5.356)

Background and Introduction

This study was initiated by our interest in chemical and physical methods of preservation of historic and archaeological earthen structures, specifically adobe. Many cultural structures are constructed of adobe, which easily loses structural integrity when wetted. Preliminary laboratory work dealt with the interaction of various chemical consolidants with adobe [1]. After isocyanates and silane esters were shown to be successful in consolidating adobe, work focused on the interaction of those consolidants with pure clays, since these are the components most affected by wetting. This phase of research involved studying the effects of specific chemical consolidants (isocyanate [hexamethylene diisocyanate (HDI)-derived polymers] and silanes) on pure clays. The results showed that treatment of clays with isocyanates and silanes markedly increased the clay's water repellency but did not consolidate the clay [2]. Although chemical treatment inhibits water uptake and partially binds the clay particles together, it does not prevent failure of individual clay particles when subjected to deformational stress.

Materials and Methodology

After failing to consolidate pure clays by chemical treatment the next step was to make an *artificial* adobe by combining three parts quartz sand (with a uniform particle size of 0.5 mm) with one part clay. This mixture resembles a "typical" adobe and, when wetted, resulted in a workable, coherent, artificial adobe material. Three sets of artificial adobe were made using three different clays obtained from the Clay Minerals Society, Source Clay Minerals Repository at the Department of Geology, University of Missouri, Columbia, Missouri. The clays are:

A) SWy-1, Na-montmorillonite, Crook County, Wyoming ;
B) SAz-1, Ca-montmorillonite, Apache County, Arizona ;
C) KGa-2, Kaolin, Warren County, Georgia.

Test plugs were manufactured by combining the sand:clay mixture with water to form a viscous slurry that was poured into small (22 mm x 40 mm) cylindrical molds. Plugs of adobe were manufactured in a similar fashion by disaggregating adobe blocks obtained from Ft. Selden, New Mexico, then reconstituting the material with water into a viscous slurry and recasting it in the cylindrical molds. Pure quartz plugs were also made by grinding the quartz sand to obtain a variable size range distribution. This was then sieved and recombined in the following proportions: <45 µm = 5%, 45 µm to 75 µm = 5%, 75 µm to 180 µm = 10%, and >180 µm = 80%. This material was then mixed with water and poured into the molds. After the molds were filled they were placed in an oven set at 50° C to dry. The resulting sand:clay, adobe, and quartz plugs were removed from the molds and given time to equilibrate with the ambient laboratory conditions (22° C, 40-50% RH).

After equilibration to a constant weight, the plugs were treated with either an isocyanate or a silane. The isocyanate (an HDI-derived prepolymer) is manufactured commercially by Mobay Corporation under the name Desmodur N-3390™ (DN-3390™) and is produced as a 90% concentration in an aromatic hydrocarbon and *n*-butyl acetate mixed solvent. Treatment required diluting the DN-3390™ with a 2:1 xylene:methyl ethyl ketone (MEK) solvent mixture to form solutions with concentrations of 5% to 25%. The silanes were tetraethylorthosilicate (TEOS, $(C_2H_5O)_4Si$), with and without methyltriethoxysilane (MTEOS, $CH_3(C_2H_5O)_3Si$), which is added to achieve water repellency. According to the manufacturer these contain 75% active solids in an acetone-MEK solvent and are produced by ProSoCo Inc. under the name Conservare Stone Strengthener H™ (SS-H, with MTEOS) and Conservare Stone Strengthener OH™ (SS-OH, without MTEOS). The silanes do not require additional mixing with solvents. The isocyanate polymerizes in situ by reacting with water inherently present in the clays to form urea linkages with release of carbon dioxide. The silanes polymerize by hydrolysis with atmospheric and in situ moisture, which creates a network Si-O polymer that ties into and

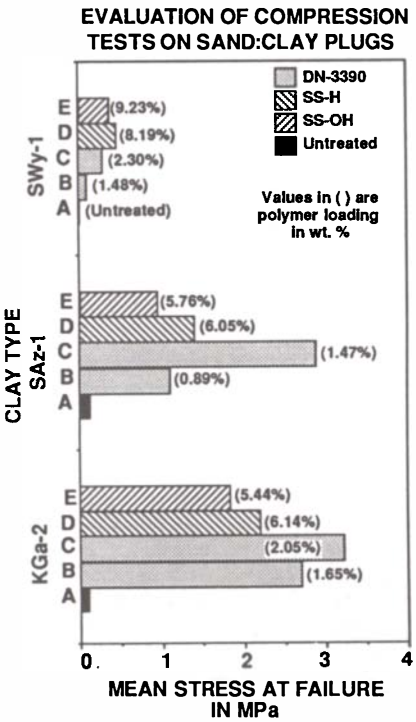

Figure 1. Results of compression tests showing mean stress at failure for untreated and isocyanate- or silane-treated sand:clay plugs.

TABLE II: Evaluation of Compression Tests on Adobe, and Quartz Plugs

Plug Type (Letter refers to figures 3 and 4)	Mean Stress & (Std. Deviation at Failure) in MPa	Mean Modulus & (Standard Deviation) in MPa
Adobe (A)	0.976 (0.170)	93.199 (46.338)
Adobe (B)	3.218 (0.668)	281.166 (118.678)
Adobe (C)	4.167 (0.877)	274.915 (53.243)
Adobe (D)	4.679 (0.667)	338.661 (50.280)
Adobe (E)	8.070 (2.236)	399.022 (97.507)
Adobe (F)	12.082 (3.342)	511.326 (78.337)
Adobe (G)	5.862 (0.884)	471.561 (15.782)
Adobe (H)	5.667 (0.723)	463.604 (88.198)
Adobe (I)	1.466 (0.431)	89.511 (14.219)
Adobe (J)	2.306 (0.318)	173.542 (41.451)
Adobe (K)	2.558 (0.595)	199.973 (19.150)
Adobe (L)	2.482 (0.474)	187.213 (18.090)
Quartz (A)	0.051 (0.015)	9.029 (6.807)
Quartz (B)	3.469 (1.401)	246.830 (156.099)
Quartz (C)	1.700 (0.391)	110.561 (58.729)
Quartz (D)	0.517 (0.134)	45.776 (15.154)

crosslinks the substrate being treated.

Each plug was treated with 3 to 6 ml of solution, then covered to inhibit solvent evaporation and permit thorough penetration of the consolidant into the plugs. After treatment and curing, the plugs were tested for compressive strength, resistance to disaggregation in water, and porosity. A set of untreated plugs was also tested to develop baseline values. Compressive strength determinations were obtained using an Instron Universal Testing Instrument, model 4201, with a 500 Kg capacity compression load cell. The samples were tested using a crosshead speed of 5 mm/minute with a sampling rate of 10 points per second. Water repellency and resistance to disaggregation by water was determined by submerging the sand:clay, and adobe plugs in water for approximately 48 hours. The plugs were removed from the water and weighed, placed in an oven at 50° C for a minimum of 48 hours, reweighed, and placed back into water. The plugs went through ten wet-dry cycles or until they began disaggregating. Mercury injection porosimetry was used for porosity measurements on small pieces (approximately one to two cubic centimeters) of treated and untreated adobe samples.

The relationship of isocyanate solution concentration and number of applications with depth of penetration and consolidation was also examined. Three isocyanate solutions (DN-3390™ + MEK) were mixed in concentrations of 25%, 12.5%, and 6.25%. Each solution was brushed onto a 16 cm x 10 cm area of an adobe block, from Ft. Selden, New Mexico, in 1, 2, 4, 8, and 16 coat applications. The treated blocks were wrapped in plastic, cured for two weeks, then uncovered and cut in half. One half was archived for future study while the other half was placed in a large container of water to wash away the unconsolidated portion.

Experimental Results

The results of compression tests for the sand:clay (*artificial* adobe) plugs are shown in table I and figure 1. Untreated *artificial* adobe plugs failed at low stress levels (0.02 MPa to 0.13 MPa) in the following order of decreasing strength, SAz-1 > KGa-2 >> SWy-1. Chemical treatment markedly increased the compressive strength of the plugs and altered the strength relationships to the following, KGa-2 > SAz-1 >> SWy-1. Both isocyanate- and silane-treated plugs exhibited between a six- to thirty-two-fold increase in compressive strength, based on mean stress values. Plugs made with clay SAz-1 exhibited a twenty-two-fold increase in compressive strength when treated with isocyanate, and a ten-fold increase when treated with the silanes. Treatment with the silanes resulted in a thirty-fold increase in compressive strength for those plugs made with clay SWy-1, whereas isocyanate treatment only resulted in a twenty-fold increase. Both isocyanate and silanes caused comparable increases in the compressive strength of plugs made with clay KGa-2.

Table II and figure 2 show isocyanate treatment of the adobe plugs resulted in a three- to twelve-fold increase in compressive strength over untreated adobe. Treatment with either silane resulted in a six-fold increase in the compressive strength relative to untreated adobe. For most of the adobe samples tested the silane-treated plugs exhibited a greater compressive strength than the isocyanate-treated plugs. However the silane loading of 4.3%-4.5% was greater than the loading on any of the isocyanate-treated samples (see figure 2). In spite of this, an isocyanate loading of 3.2% resulted in a greater increase in compressive strength than was observed for the silane-treated samples. This, together with the results in table I and figure 1, indicate that at equivalent loadings the isocyanates would be superior to the silanes for enhancing the compressive strength of *artificial* and natural adobe.

Table II and figure 2 also show that wet, isocyanate-treated adobe has a compressive strength similar to dry, untreated adobe. Isocyanate-treated adobe subjected to multiple wet-dry cycles is weaker than a similarly treated adobe not exposed to wet-dry cycling, although it still remains stronger than the initial untreated adobe. The compressive strength of untreated and treated pure quartz plugs is also presented in table II and figure 2. Isocyanate treatment increased the compressive strength of the quartz plugs eighty-fold, whereas silane treatment resulted in a ten- and thirty-three-fold increase (SS-OH and SS-H, respectively).

Figure 3 demonstrates how chemically treated sand:clay and adobe plugs withstood disaggregation in water relative to untreated plugs, and to each other. Untreated adobe and plugs made with quartz sand and clay SAz-1 or KGa-2 (Ca-montmorillonite

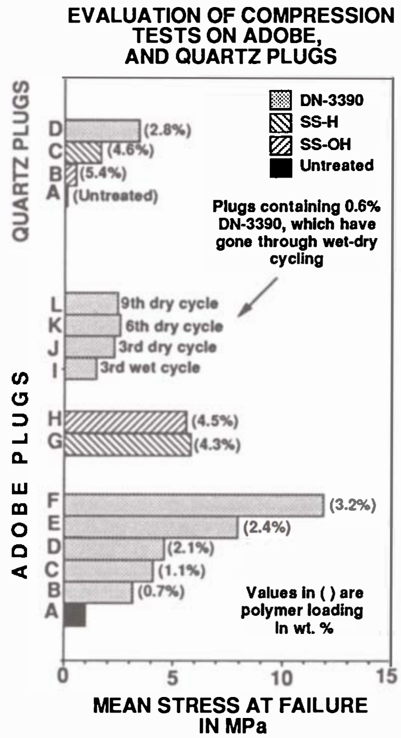

Figure 2. Results of compression tests showing mean stress at failure for untreated and isocyanate- or silane-treated adobe, and quartz plugs.

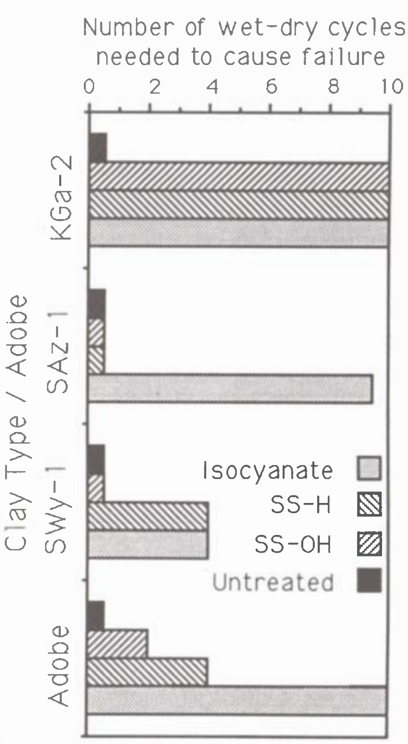

Figure 3. Graph showing relationship between clay type or adobe, type of chemical consolidant, and number of wet-dry cycles needed to initiate disaggregation.

and kaolin, respectively) disintegrated as soon as they came in contact with water. The plug made with clay SWy-1 (Na-montmorillonite) did not disaggregate; instead it absorbed water and swelled into a gelatinous mass. Figure 3 also shows that plugs made with kaolin were very resistant to disaggregation by water once they had been chemically treated, regardless of the type of consolidant used. Isocyanate treatment provided excellent resistance to deterioration by water for the adobe plug and only slightly lesser protection for the sand:clay plug made with clay SAz-1 which deteriorated during the tenth wet-dry cycle. However, the isocyanate and SS-H had limited success in preventing disaggregation of the plugs made with clay SWy-1 which began disaggregating after four wet-dry cycles. In contrast, SS-OH provided very little protection against deterioration by water for the sand:clay plug made with clay SWy-1. Neither of the two silanes provided protection for plugs made with clay SAz-1. However, both silanes were partially successful in protecting the adobe plug against rapid deterioration by water, with SS-H outperforming SS-OH.

The evaluation of polymer concentration and number of applications with depth of penetration revealed that the deepest penetration was attained by applying sixteen coats of the most dilute (6.25%) solution. Figure 4 shows the difference in depth of penetration between natural adobe blocks treated with the 6.25% solution and the 25% solution. Sixteen coats of the 6.25% solution consolidated approximately 920 cc of adobe, while similar applications using concentrations of 12.5% and 25% resulted in consolidation of 680 cc and 470 cc of adobe, respectively.

Porosity measurements, using mercury injection porosimetry, were made on a number of treated and untreated adobe plugs. The porosity of untreated samples varied, ranging from 13% to 25%. Porosity measurements of the treated plugs also fall within this range. Because of this, no difference in porosity was distinguished between untreated and treated samples. However the small volume of the test specimens is probably insufficient to ensure statistical homogeneity, and air voids could easily account for the wide range of values

Discussion

Tables I and II and figures 1 and 2, show that the compressive strength of adobe is far greater than that of sand:clay plugs. This is believed to be a function of the grain size distribution and composition. Natural adobe is made of particles with a wide grain size distribution ranging from pebble- or granule-size down to clay-size. Therefore the particles are closely packed with abundant grain-to-grain contacts, minimal pore space, and good cohesion. In addition, much of the adobe material is composed of hard, resistant particles such as quartz or feldspar. When this material is treated with isocyanate or silane esters, a particle-to-particle bond is formed by the polymer which glues the mass together and enhances the cohesiveness of this naturally strong, coherent material. In contrast the sand:clay plugs contain material with two distinct grain sizes: sand-size and clay-size. The sand-size quartz particles are very strong and coherent particles that provide most of the structural strength of the plugs. However, the clay particles, which are inherently weaker, act primarily as binder or filler between the quartz grains. Compared with adobe, this type of mixture has fewer grain-to-grain contacts, more pore space, and is an inherently weaker material that can fail easily. The difference between adobe and sand:clay plugs is shown in figure 5. When sand:clay plugs are treated with isocyanate or silane esters the polymer bonds to the quartz grains and to the outer surfaces of the clay particles. However polymer cannot penetrate between individual clay layers and plug failure occurs by delamination of the clay layers when subjected to deformational stress.

The effect of grain size and composition is further demonstrated by the enhanced compressive strength of consolidated pure quartz plugs, as shown in figure 2 and table II. The initial strength of the plugs, which is similar to that of sand-clay plugs, is due to the quartz grains and a weak cohesion between the variable-sized particles. However, the compressive strength of treated pure quartz plugs more closely approximates the compressive strength of treated adobe plugs. This is probably because the initial strength of the quartz particles is enhanced by the supporting silica-polymer network.

This research shows that the treatment of sand:clay and adobe plugs with isocyanate and/or silanes results in consolidation and enhances the ability of the plugs to resist rapid deterioration by

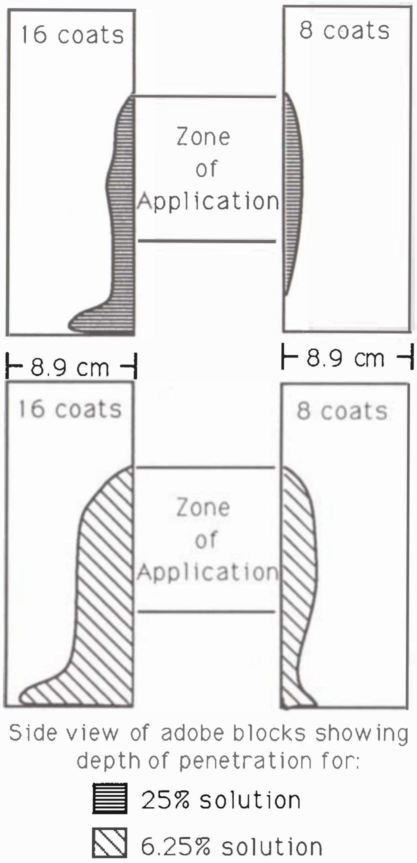

Figure 4. Cross-sectional views of adobe blocks showing depth of consolidation for a 6.25% solution (diagonal pattern) and a 25% solution (horizontal pattern) of isocyanate using 8 coats and 16 coats.

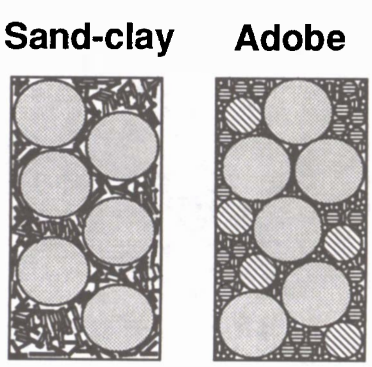

Figure 5. Schematic representation of sand:clay and adobe plugs showing differences in grain-to-grain contacts, packing and porosity.

exposure to water. In sand:clay plugs, the degree of resistance to deterioration appears to be controlled by the clay mineralogy and type of consolidant used. Isocyanate attaches itself to polar sites that cover the basal surfaces of montmorillonites [3,4]. Polar sites are also present on the surface of quartz and kaolin particles in the form of a water film. This provides numerous attachment sites that enable the isocyanate to form strong bonds between clay and quartz particles. Silanes attach by ligand exchange with OH molecules that occur on the basal surface of kaolin particles and on the edges of montmorillonites [4]. Although ligand bonding of the silanes is stronger than the van der Waals and ion-dipole forces of the isocyanate bonding, the sheer number of polar attachment sites appears to allow the isocyanate to develop a stronger overall bonding than the silanes [4]. Because silanes do not develop a strong enough bond bridging quartz and montmorillonite particles, plugs made with those materials are easily deteriorated by the physical movement of clay particles as they hydrate and dehydrate. This explains why silanes did not perform well on montmorillonite-bearing plugs, but did perform well on kaolin-bearing plugs. In contrast, isocyanate develops a bond strong enough to prevent or diminish the deterioration of the sand:clay plugs by the hydration-dehydration action. This permits the isocyanate to perform better at protecting the plugs against deterioration by water.

The lack of difference in porosity of untreated and treated samples is probably because neither isocyanate nor the silanes are heavily loaded into the samples. These polymers form thin films over the surfaces of the clay and sand particles instead of filling the pore spaces with polymer, which is commonly the case with some chemical consolidants. If sufficient polymer was applied, a porosity distinction would be recognized because the pores would become clogged. However, this could be as or more destructive to adobe than leaving it untreated. Isocyanate inhibits deterioration by water but allows water to pass through the adobe, thereby preventing water from becoming trapped in the adobe and causing internal damage. This also explains why the isocyanate works so well on adobe.

Increased penetration and consolidation as a function of solution concentration and number of applications is also related to the above. At high concentrations the polymer solution becomes too viscous to permit adequate penetration into the adobe. By applying multiple coats of dilute solutions the polymer can penetrate deeper into the adobe substrate. If more concentrated solutions were used, the polymer could become concentrated at or near the surface. This would result in the surface becoming sealed against additional treatment and could also trap water introduced through capillary rise from the ground. This, in turn, could cause accelerated deterioration of the interior of the adobe and lead to premature collapse of the adobe wall or structure.

Summary

Isocyanate and silanes have been shown to enhance adobe's resistance to disaggregation by water, as well as increasing compressive strength. However, the adobe's composition and grain size distribution are important factors to consider when deciding which consolidant to use. It appears that adobes containing kaolinite are effectively consolidated with silanes, whereas those adobes containing montmorillonite, and/or mixed-layer clays, respond better to isocyanate.

Successful treatment is also related to the polymer solution concentration, and depth of penetration. High polymer concentrations, or inadequate penetration, could result in the development of a polymer-rich outer skin. This could cause accelerated deterioration of the adobe by separation of the treated, outer layer from the untreated inner core. This type of phenomenon has been observed on several isocyanate-treated test walls at Ft. Selden, New Mexico, where the consolidated outer surface has detached from the rest of the wall. This is believed to be a result of the difference in the coefficients of expansion, upon wetting, between the untreated and treated portions of the adobe. This type of behavior was not observed for silane-treated test walls, possibly because the silanes permit more expansion of the adobe than does the isocyanate. This indicates that to successfully treat adobe, or earthen structures, it is necessary to insure deep penetration and prevent development of a rigid, non-expandable outer skin.

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THE GETTY ADOBE RESEARCH PROJECT AT FORT SELDEN III: AN EVALUATION OF THE APPLICATION OF CHEMICAL CONSOLIDANTS TO TEST WALLS

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ABSTRACT

Silane esters and polyisocyanates were applied to adobe test walls in various concentrations and solvent mixtures by spraying, brushing, multiple coating, and bulk infiltration. After one month's curing they were subjected to an accelerated weathering regime of two water spray cycles per day for two months, and subsequently they were allowed to weather naturally. The walls were evaluated visually according to a numerical rating system. Isocyanates provide very effective stabilization by a combination of brushing and bulk infiltration, but there must be a suitable network of accession holes for deep delivery of polymer, and the amount of consolidant must be optimized. The silane ester formulation, Stone Strengthener H, is easier to apply and gives good consolidation without discoloration; but the treated walls show erosion not seen with isocyanate treated walls. Old, aged adobe may require a rehydration before either consolidation can be done.

KEYWORDS

Adobe, brushing, bulk infiltration, consolidation, dilution effects, isocyanates, mud brick, rehydration, silanes.

Introduction

This study is concerned with the evaluation of chemical consolidants used to stabilize old, weathered adobe of historical interest. Adobe test walls were treated with different chemicals by a variety of application strategies and after curing were subjected to a daily schedule of direct water spraying for two months. This is very severe treatment for adobe. It provided highly accelerated weathering and enabled us to evaluate materials and procedures in a relatively short time period.

Test Wall Evaluation

In the winter of 1988, twenty-five adobe walls were constructed at Fort Selden, New Mexico. Bricks, 30 centimeters (12 inches) square and 10 centimeters (4 inches) thick, were made from local clay-bearing soil which contained 91% sand and 8% silt and clay. The clay consisted of roughly equal amounts of kaolinite, illite and smectite. These bricks were made into east-west running walls 150 centimeters (five feet) long and tall and 30 centimeters thick, with a mortar of the same composition. The walls stood on two layers of adobe brick below grade. On each side a surface "plaster" coating made from the same mortar was trowelled over the right half of the wall, i.e., an area 150 centimeters (5 feet) in height and 75 centimeters (2.5 feet) in width. The walls were allowed to weather naturally for several months and in May were treated with a number of consolidants. After treatment they were wrapped in polyethylene sheeting and allowed to cure for one month and then subjected to water spraying for two months. On each side a nozzle four feet from the wall delivered 22 liters of water over a 15 minute period twice a day as a dispersed spray. In addition, these outdoor walls experienced an unusually rainy New Mexico summer. Photographs of northern and southern exposures of some of the walls treated with DN 3390 or silane esters are provided in the left columns. They can be matched with descriptions of treatments in Tables 3 and 4.

Chemicals and Application Procedures

Most of the studies focused on two types of consolidants: polyisocyanates and silane esters. Most of the isocyanate studies were done with DN3390, is an isocyanurate trimer of hexamethylene diisocyanate. It is supplied as a 90% concentration in a mixture of n - butyl acetate and aromatic hydrocarbons. Stone Strengthener H (SSH) is a mixture of methyl triethoxysilane and tetraethoxysilane (ethyl silicate) in a ketone solvent, and it contains dibutyltin dilaurate as catalyst. The active component in Stone Strengthener OH (SSOH) is ethyl silicate. The isocyanates were given to us by the Mobay Chemical Company while SSH and SSOH were donated by ProSoCo and applied to certain test walls by their personnel.

Both types of chemicals seem uniquely suited for adobe because they cure by mechanisms that involve water inherently available in clay. The silane esters hydrolyze to a silicate network that can crosslink appropriate siliceous functionality in the adobe while polyisocyanates readily link up and consolidate in the presence of water through polyurea formation.

Application was generally done by brushing, but spraying or bulk infiltration were used in a number of cases. Bulk infiltration is a procedure in which holes are drilled into the adobe wall and funnels are used to supply the consolidant; This insures that impregnation at a substantial depth is obtained. Where bulk infiltration is used, surface application of consolidant by brushing is also employed.

Generally, no two walls were treated by exactly the same procedure. Treatment of wall 18 with DN3390 by a combination of bulk infiltration and brushing gave the best stabilization, and its description may be illustrative. Four evenly spaced 19 millimeter diameter holes were drilled across the top to a depth of 30 centimeters. Similarly four holes, one meter above the base, evenly spaced horizontally on the south side and one hole at each end, were drilled downward at 45° angles. Also a series of holes was made at 15 centimeter intervals around the base. A solution of 9 liters of DN3390 in 27 liters of methyl ethyl ketone and 27 liters of toluene was prepared. Funnels were used to deliver 12 liters of this solution through the top holes, 8 liters through the side holes and 28 liters to the base holes. Twelve liters were brushed on the surface in five coats, and an additional 3 liters was applied around the base. The treated adobe was then tightly wrapped in polyethylene film for four weeks.

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Evaluation of the effectiveness of consolidation was done as soon as the spraying was concluded, then three months later, and finally after an additional twelve months. Subjective quality ratings, ranging from zero for a collapsed wall to ten for an unblemished wall, were made separately for brick surfaces (Table 1) and adobe mud coated surfaces which are described as "plaster covers" (Table 2). Separate rating systems were needed because walls with plaster coats tended to deteriorate by having the cover pull away from the surface while the brick surfaces cracked and eroded. At the conclusion of spraying, one of us (CS), who was not involved in the treatment, created the rating system by a general, overall survey of the test walls. The evaluation was carried out by an examiner (CS) who did not know the procedures that had been used on the particular wall being rated. The Getty Conservation Institute's overall program at Fort Selden looked at a number of stabilization approaches, including the use of inserted rebars, protective geotextiles and reburial procedures, but this presentation will consider only the evaluation and comparison of chemicals used for consolidation.

TABLE 1

RATING ON ADOBE WALL

RATING VALUE	DESCRIPTION
10	No sign of deteriorstion of any kind
9	Single, small crack
8	Several minimal cracks
7	Wall looks strong, intact but many cracks
6	Poorer than 7
5	Extensive cracking
4	Extensive cracking, some erosion
3	Extensive cracking, heavier erosion
2	Material fallen from wall
1	Extensive amount of fall-off
0	Collapse

TABLE 2

RATINGS ON PLASTER COVER

RATING VALUE	DESCRIPTION
10	No sign of deterioration
9	A few cracks, no sign of separation
8	More cracks - a suggestion of separation
7	Partial separation, not visible, but discernable by tapping - modest cracking
6	Extensive pulling away discernable by tapping, not visible, heavier cracking
5	Partial separation is visible
4	Total separation is visible
3	Plaster is ready to Fall off
2	Parts of plaster cover has fallen off
1	The plaster cover has completely fallen off
0	The wall has collapsed

Results with the Isocyanate, DN3390

The results of this study are summarized in Table 3, which is concerned with the isocyanate DN3390, in Table 4, which examines the consolidation of adobe with silane esters, and in Table 5 which compares different types of isocyanates. Results which describe the effectiveness of DN3390 are developed by comparing the ratings of five treated walls (16 through 20) with an untreated wall. The untreated wall, wall 21, had all but washed away by the time spraying had ended, but the treated walls were relatively intact and standing (Table 3). There was considerable variation in the quality of these consolidated structures. Wall 18 was essentially unchanged while wall 19 was badly cracked and eroded. The critical difference between the walls was the use of bulk infiltration which provided very deep penetration. Wall 18 had access holes drilled across the top, in the midsection and around the base and the largest amount of consolidant, 9 liters, was used. The second best wall, wall 20, had infiltration holes only across the top and along the base and employed much less consolidant, 3 liters. This wall received a rating of 28 (out of a possible maximum of 40) versus a value of 37 for wall 18. The plaster layer on the south side of wall 20 had pulled away, not at the top but in the lower part of the wall. These findings suggest that good results can be obtained with less consolidant but that broader placement of infiltration holes is important. In the walls where only brushing was used, and where there was no direct deep placement of consolidant, results were poorer. There was more cracking and breaking off of adobe. Generally, the peeling away of the plaster coat was a more critical and noticeable problem than the deterioration of the brick surface.

Studies were made on the depth of penetration achieved by brushing. Samples of adobe powder were obtained at measured distances from the surface by drilling. In laboratory studies, these were brought to constant weight at 150°C to drive off water and then heated at 600°C in air to burn off the polymer. Weight and concentration of polymer were then determined by difference. A sample result for wall 17 is shown in Figure 1. This wall had 4 liters of DN3390 brushed over the top and sides, which is a relatively large amount. Typically polymer concentrations between one and two percent are found within the outer inch of adobe. Very much less occurs between one to two inches from the surface, and essentially no polymer can be found any deeper. We did notice in other studies that when large amounts of solution are used on upper surfaces, polymer is found deeper into the brick at lower levels of the wall.

Wall 21 North

TABLE 3

COMPARISON OF THE CONSOLIDATION OF ADOBE WALLS WITH DN3390 USING DIFFERENT AMOUNTS OF ISOCYANATE AND DIFFERENT APPLICATION STRATEGIES[A]

WALL	AMOUNT OF DN3390			DELIVERED IN LITERS			SUMMARY OF RATINGS				
	TOTAL	Brushed on Top & Sides	Applied To Base	INTERNAL BULK DELIVERY[B] TOP	MIDSECTION	BASE	NORTH BRICK	NORTH PLASTER	SOUTH BRICK	SOUTH PLASTER	TOTAL RATING
16	3.0	2.0	1.0	0	0	0	5	5	7	5	22
17[C]	4.5	4.0	0.5	0	0	0	7	4	8	4	23
18	9.0	1.7	0.5	1.7	1.1	4.0	10	9	9	9	37
19	4.5	1.5	0	0	0	3.0	5	4	4	2	15
20	3.0	1.0	0.5	0.6	0	0.9	9	4	7	8	28
21	none	0	0	0	0	0	1	1	1	1	4

A. All runs (except 17) at 12.8% DN 3390 in equal volumes of methyl ethyl ketone and mixed xylenes. No catalyst was used.

B. Material delivered into deeply drilled holes by using funnels.

C. Approximately one-third of the DN 3390 was at 6.4% concentration.

Wall 21 South

Wall 19 North

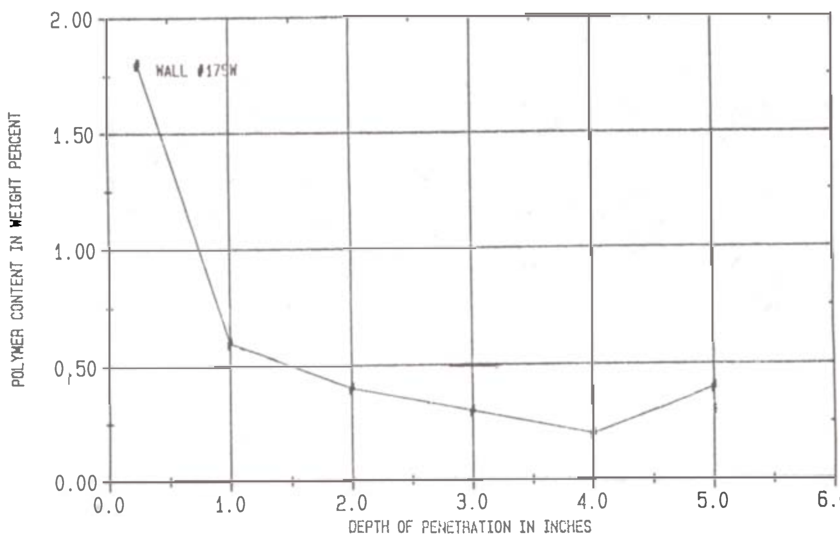
Wall 19 South

Wall 18 North

FIGURE 1

POLYMER CONTENT DETERMINATIONS

WT. % DN3390 -vs- DEPTH OF PENETRATION



POLYMER CONTENT FOR WALLS # 17SW

The runs in Table 3 show that, in general, better results are obtained with brushing when more consolidant is used. Our results also indicate that it is better practice to apply more solution at the upper sides and top rather than to drench the base. This is confirmed by comparing walls 17 and 19. In each case 4.5 liters of DN3390 were delivered. In wall 17, 4.0 liters were put onto the top and sides and 0.5 liters to the base. For wall 19, 3.0 liters were put into the base by bulk infiltration, and only 1.5 liters were used on upper surfaces. Wall 19 showed the poorest consolidation of any of the walls treated with DN3390. Overall the studies show that the isocyanate can provide effective consolidation of adobe, but there must be a suitable network of accession holes for bulk infiltration of polymer and the amount of consolidant must be optimized.

Results with Silane Esters

Eight test walls were used to examine the ability of silane esters to stabilize adobe. Table 4 outlines the results where SSH was used on five walls, SSOH on two walls, and SSH in a different solvent, mineral spirits, on a single wall. All of these systems used 0.5% dibutyltin dilaurate as catalyst. In six of the series, application was by brushing or by a combination of brushing and bulk infiltration. This was done in a manner to attempt to replicate the application procedures used with DN3390. In two cases the silane esters were delivered to the wall by spraying.

TABLE 4

COMPARISON OF THE CONSOLIDATION OF ADOBE WALLS WITH SILANE ESTERS USING DIFFERENT AMOUNTS OF CONSOLIDANT AND DIFFERENT APPLICATION STRATEGIES

WALL	SILANE[A] ESTER	METHOD OF DELIVERY	TOTAL	AMOUNT DELIVERED IN LITERS BY BRUSHING TOP & SIDES	BY BRUSHING BASE	BULK INFILTRATION TOP	BULK INFILTRATION MIDDLE	BULK INFILTRATION BASE	RATINGS NORTH BRICK	NORTH PLASTER	SOUTH BRICK	SOUTH PLASTER	TOTAL
22	SSH	BRUSHING	19.5	8.8	0.7	0	0	0	5	6	7	7	25
23	SSH	SPRAYING	18.5	18.5	0	0	0	0	6	7	7	7	27
24	SSH	BULK[B] AND BRUSHING	45	13	2	6	10	14	7	7	6	8	28
25	SSH	BRUSHING	22	10	12	0	0	0	7	6	7	8	28
26	SSH	BULK AND BRUSHING	18.5	7.5	1.5	6.5	0	3.0	4	6	5	8	23
29	SSOH	SPRAYING	18.5	18.5	0	0	0	0	5	5	4	0	14
30	SSOH	BULK AND BRUSHING	18.5	11.5	2	10	0	5	0	0	0	0	0
31	SSH[C]	BRUSHING	9.5	8.8	0.7	0	0	0	8	7	8	8	33

A. All runs (except 31) in polar, ketonic solvent. All runs contained catalyst.

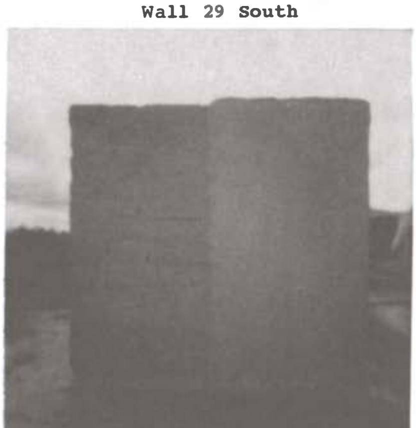
B. Bulk indicates material was delivered into deeply drilled holes by using funnels.

C. In mineral Spirits

Wall 18 South

Wall 29 North

Wall 29 South



Wall 25 North

In general it was found that SSH was effective while SSOH was not. This is not unexpected since the major property difference provided by the two is water repellency. The formulation containing methyl triethoxysilane gives a surface that rejects water, while the formulation without the alkyl silane, the SSOH, does not, and this makes a critical difference when attack is by spraying water. There seemed to be little difference between walls that were treated by spraying, brushing or the combination of brushing and bulk infiltration. The walls treated with SSH retained their original light tan color and showed no pulling away of plaster coats. We attempted to determine why these layers peeled away from some of the isocyanate treated walls but did not, in any case, do so when the consolidant was SSH. Thermal expansion studies done by thermomechanical analyses showed no differences between samples treated with DN3390 and SSH. However, comparison of swelling coefficients by the same procedure suggests that adobe treated with SSH is less rigid; this may explain the difference. We do not have the technology to measure low polysiloxane concentrations in adobe and thereby obtain the depth of SSH penetration. The general correlation of non-peeling with the amount of consolidant suggests that stability is also a matter of getting sufficient material deeply enough into the structure.

The SSH treated walls all received a good total rating that appears to be independent of the amount of consolidant used or the method of application. This is in obvious contrast to results obtained with DN3390. The low viscosity of the silane esters enables large amounts to be applied with ease and to achieve good penetration, which is an important advantage. The total quantity of the consolidant itself applied in the silane ester tests ran from 9.5 to 45 liters, a range that was totally above that of the 3 to 9 liters used in DN3390 runs. This may explain why results with the isocyanate tests were more dependent on the amount of consolidant and the method of application.

The main problem with walls treated with SSH and a major difference in the results obtained with isocyanates was their tendency to show surface erosion. Originally the adobe brick walls had a relatively smooth appearance. After treatment with isocyanates and subsequent exposure to water, the surfaces generally still retained a flat, even quality. They were darker and, depending on the amount of DN3390 applied, sometimes were cracked. The surfaces had become hardened but were otherwise structurally unchanged. In contrast, the silane ester treated surfaces were grainy and eroded and in some cases showed ruts and cracks. This difference in behavior is probably generally true in stone consolidation, i.e., where silane esters are compared to thermoset resins like epoxies and isocyanates for the stabilization of sandstone and limestone, but only in the regime of water attack on treated adobe can this be discerned so clearly and so quickly.

The best result in this series was obtained with SSH in a mineral spirits solvent, rather than the more conventional cosolvent, (approximately 20% methyl ethyl ketone - 10% acetone). Mineral spirits is a petroleum distillate consisting of aliphatic and aromatic hydrocarbons. Wall 31, which was treated with the silane in this solvent, received a rating of 33 while wall 22, treated identically except for the use of the mixed ketone solvent, had a rating value of 25. We were able to smell residual aromatic hydrocarbons in the test walls after spraying was stopped. It is likely that the better performance observed in wall 31 resulted from the presence of heavier hydrocarbons, which provided additional water barrier and repellency properties.

TABLE 5
COMPARISON OF THE CONSOLIDATION OF ADOBE WALLS
USING DIFFERENT TYPES OF DIISOCYANATES AND DIFFERENT AMOUNTS OF CONSOLIDANT

WALL	CONSOLIDANT	POUNDS OF CONSOLIDANT USED IN HALF WALL[A]	PLACEMENT OF CONSOLIDANT[B] TOP & SIDES	BASE	RATINGS NORTH BRICK	NORTH PLASTER	SOUTH BRICK	SOUTH PLASTER	TOTAL[E]
33W	Diphenylmethane diisocyanate	3.8	3.4	0.4	7			5	24
33E	Dicyclohexylmethane diisocyanate and catalyst[C]	3.2	2.6	0.6		6	4		20
34E	DN 3390[D]	7.2	7.2	-	8			5	26
34W	DN 3390[D]	1.8	1.8	-		3	3		12
35W	Dicyclohexylmethane diisocyanate[D]	1.8	1.8	-		2	4		12
35E	Dicyclohexylmethane diisocyanate[C]	7.2	7.2	-	7			5	24

A. Each quantity of consolidant was dissolved in a mixture of 4.5 liters of methyl ethyl ketone and 4.5 liters of mixed xylenes.

B. Application was by brushing on of 2 to 6 coats.

C. Approximately 3.0 milliliters of dibutyl tin laurate was added to solution.

D. Approximately 0.5 milliliters of dibutyl tin laurate was added to solution.

E. Total is calculated on a full wall basis.

Wall 25 South

Results with Other Consolidants

Other isocyanates examined in this program were diphenylmethane diisocyanate and dicyclohexylmethane diisocyanate. Both are commercial products marketed by Mobay. Results outlined in Table 5 show that these worked about as well as DN3390. This table also demonstrates that the use of optimum amounts of impregnant is needed for good consolidation. In one set the east half of wall 34 was treated with 7.2 pounds of DN3390, while the west half received only a quarter of that amount or 1.8 pounds. Respective summary ratings of 26 and 12 illustrate the benefits of using a sufficient amount of consolidant. Almost comparable results were obtained when dicyclohexylmethane diisocyanate was used in a similar manner. These experiments are additional evidence of the criticality of the amount of isocyanate employed and the lesser importance of the type of polyfunctional isocyanate that is used.

Two additional treatments should be mentioned. Wall 32 was treated by brushing and bulk infiltration with 4.4 pounds of Acryloid A-21 dissolved in 50 liters of a mixed solvent consisting of methyl ethyl ketone, xylenes and butyl acetate. During the two months of water spraying this wall collapsed. Wall 36 was treated with 3 liters of DN 3390 in much the same way that treatment was carried out on wall 16 except that half of the methyl ethyl ketone in the cosolvent with xylene was replaced with butyl acetate, and 3 milliliters of dibutyltin laurate, catalyst, was added. A summary rating of 26 for this wall suggests that neither factor had a major impact on the quality of the treatment.

Reevaluations at Later Periods

Reevaluations of all of the walls was done three months and then fifteen months after the initial assessment. A sample of the reevaluation of 10 walls is shown in Table 6. Walls treated with both isocyanates and silane esters are included. These data show that during the year and a quarter after the water spraying there was no additional deterioration. An exception to this occurred with walls where the plaster coatings had pulled away. This behavior led to initial ratings of 3 or 4. In most of these cases this separated layer subsequently fell off to mandate a drop in rating to a value of one. The ratings, each time, were done without considering the treatment. The consistency of the ratings over time provides validation of the evaluation procedure.

TABLE 6

REEVALUATION OF WALLS THREE MONTHS AND FIFTEEN MONTHS AFTER THE END OF SPRAYING

WALL	AMOUNT OF CONSOLIDANT TO TOP & SIDES, LITERS			NORTH FACE		SOUTH FACE		SUMMARY RATING
	TYPE	SURFACE	BULK	BRICK	PLASTER	BRICK	PLASTER	
MONTHS --------->				0 3 15	0 3 15	0 3 15	0 3 15	0 3 15
16	DN3390	2.3B	0	5 6 6	5 6 6	7 8 8	5 5 6	22 25 26
17	DN3390	4.0B	0	7 7 8	4 4 4	8 7 7	4 1 1	23 19 20
18	DN3390	1.7B	2.8	10 10 10	9 9 9	9 10 10	9 9 9	37 38 38
19	DN3390	1.5B	0	5 7 7	4 3 1	4 6 6	2 1 1	15 17 15
20	DN3390	1.0B	0.6	9 9 9	4 5 5	7 8 9	8 8 8	28 30 31
23	SSH	18.5S	0	6 7 7	7 8 7	7 7 5	7 7 7	27 29 26
29	SSOH	11.5S	10	5 4 5	5 5 6	4 5 4	5 5 6	19 19 21
31	SSH[M]	8.8B	0	8 6 7	7 5 8	8 7 7	8 7 8	31 25 30
35W[D]	DCHM	1.5B	0		2 3 3	4 4 4		12 14 14
35E[D]	DCHM	6.0B	0	7 7 8			5 5 5	24 24 26

B. Applied by brushing

S. Applied by spraying

M. Dissolved in mineral spirits instead of ketone solvents.

D. On wall 35E and 35W, the amount of consolidant and the summary ratings were doubled to compare on a full wall basis.

More Recent Study of Brushing Procedures

A second set of five test walls was treated with the isocyanate DN 3390 in May 1989. The purpose of this test series was to determine if the high quality of consolidation that was achieved by bulk infiltration in the previous test wall program could be obtained simply by brushing. The strategy was to use more dilute solutions of DN 3390 in order to obtain deeper penetration. The use of lower concentrations meant that a larger number of brushings (more than the seven applications typically used in the earlier set) would be required to supply the quantity of isocyanate needed for a very good consolidation.

Table 7 summarizes the results obtained in this phase and shows the amount of DN 3390 as liters of isocyanate without solvent. These studies were done on quarter and half wall segments in order to examine more variables, but the quantities of consolidant are standardized to a full wall value to simplify comparison with earlier studies. The number of brushings was relatively low in the first two wall treatments (52 and 53) but rose to 11 on wall 54 and 18 on walls 55 and 56. Correspondingly the concentrations, which are not shown, range from 12.8% to 2%.

TABLE 7

CONSOLIDATION QUALITY RATINGS ON FIVE NEW TEST WALLS

Wall	DN3390 per full wall liters	Solvent	Number of Applications	Post Wetting Solvent	Catalyst	RATING Brick	Plaster	Summary Full Wall Basis
52W	3.0	M	6	M	No	6	9	30
52E	3.0	M	6	X	No	7	4	22
53W	1.5	M	4	M	Yes	0	0	0
53E	1.5	M	4	X	Yes	7	5	24
54W	2.3	M	11	none	No	5	2	14
54E	2.3	M	11	none	Yes	0	0	0
55WW	5.2	M+B	18	B	No	9	5	28
55WE	5.2	M+B	18	none	No	9	5	28
55EW	5.2	M	18	none	No	7	8	30
55EE	5.2	M	18	M	No	7	8	30
56WW	2.6	M+B	18	B	No	7	5	24
56WE	2.6	M+B	18	none	No	7	5	24
56EW	2.6	M	18	none	No	7	8	30
56EE	2.6	M	18	M	No	7	8	30

Catalyst was dibutyl tin laurate
M = methyl ethyl ketone
X = mixed xylenes
B = butyl acetate

The rating system applied to these walls after one month of being wrapped in plastic following treatment, two months of water spraying, and three months of natural exposure is also provided in Table 7. Before discussing the numerical ratings, it should be noted that these five walls were plagued with problems that did not seem to beset the original walls. The walls, as delivered by the contractor before treatment was applied, were of poor quality with much erosion and cracking. Apparently some patching was done, but it was not sufficient. The left half of wall 53 and the right half of wall 54 rather quickly collapsed when the water spray program was employed. These massive failures made no sense based on the nature of the treatment. They may have resulted from residual deep cracks that permitted spray water to penetrate through the consolidation to the core of the wall with the obvious disastrous results. These walls may also have suffered from an inadequate amount of consolidant around the base.

Nevertheless, this phase still provided information on the effectiveness of multiple low concentration applications. Failed walls were those using the smallest amount of consolidant, 1.5 and 2.3 liters. Walls treated with higher levels of consolidant, 2.6 to 5.2 liters, all remained intact. The use of a very large number of brushings, 18, gave treated wall ratings of 30, even with the application of only 2.6 liters of DN 3390, a relatively small amount. It does appear that multiple coatings with dilute systems will give better results than fewer brushings at higher concentration, but the consolidation is not as good as the optimum use of deep bulk treatment.

The Consolidation of Aged Adobe

The purpose of this research was to develop proceedings and formulations to consolidate aged, weathered adobe of structures of historic importance. In the course of time, adobe exposed to the atmosphere becomes weak and friable. Presumably the clay platelets, initially flocculated and aligned, become more dispersed. Void spaces are enlarged which leads to a weakening of the weathered surface. We tried several brushing experiments on small, nineteenth century adobe remnants at Fort Selden. Both DN 3390 and SSH were used. To our dismay, the aged adobe took up the consolidants but was not mechanically strengthened. Working with both Fort Selden adobe and a tan adobe from Tel Dan in Israel we have found that when the adobe is recast into mud bricks and dried, it can be consolidated under treatment conditions that fail with adobe structures that had been in existence for some time. We theorize that a slow dehydration takes place that takes the clay to a form that prevents the water-based curing mechanism from occurring. To test this hypothesis, a chunk of old Fort Selden adobe was soaked with 10% aqueous methyl ethyl ketone. This permitted a rehydration without physically altering the shape of the adobe. After the organic solvent evaporated, the piece was treated with 12% DN 3390 in methyl ethyl ketone and xylene. The product, after curing and drying, was mechanically strong and hard. Thus we have qualitatively demonstrated that historic adobe can be consolidated with isocyanates and silane esters, but the need for rehydration indicates that considerable research and development remains before on-site procedures can be recommended.

ACKNOWLEDGEMENTS

We wish to thank ProSoCo Incorporated and Frances Gale of that company and Michael Jakstis and Dr. Stanley Siranovich of the Mobay Chemical Company for the donation of generous quantities of their products and their help in the use of these materials. This work was done in collaboration with Michael Taylor and the Museum of New Mexico. We are particularly grateful for the assistance of Jose Guzman, Elva Melandrez and Jaime Romero at Fort Selden.

The Preservation of Prehistoric Mud Plaster at Mesa Verde National Park

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ABSTRACT

Mud plaster is frequently found in prehistoric sites within the American Southwest. Mesa Verde National Park, a unit of the United States National Park Service, contains over 3,930 recorded archeological sites. Approximately 590 of these are cliff dwellings. More than 600 years after abandonment, many of the sandstone masonry walls in these buildings retain at least remnants of original mud plaster.

This paper discusses the multi-faceted plaster preservation program being formulated at the park. Initial steps included reviewing archival materials and thoroughly surveying extant plaster in eighteen cliff dwellings, containing over one thousand architectural spaces. Surveys of mud plaster on this scale are unprecidented in the United States. Survey methodology, results, recommended management actions, and future research needs are discussed. Additionally, the results of preliminary studies of the mineralogical characteristics of the mud plaster from Mesa Verde are presented.

KEYWORDS

Archeology, Anasazi, cliff dwellings, mud plaster, plaster conservation, Mesa Verde National Park

INTRODUCTION

Mesa Verde National Park, established in 1906, is the only National Park in the United States National Park Service created expressly to preserve cultural resources. Mesa Verde is noted for its wealth of archeological resources, particularly its cliff dwellings. The resources are of international significance, and in 1978 the park was selected as a World Heritage Site.

Of the 3,932 archeological sites recorded within the park, nearly 600 can be classified as cliff dwellings [1]. The majority are "sites of the Mesa Verde Branch of a Formative Culture known as Anasazi" [2]. The Anasazi resided throughout the four-corners region, an area where four state boundaries meet in the American Southwest. They lived in what is now Mesa Verde National Park from approximately A.D. 450 until the area was abandoned around A.D. 1300. Village locations shifted from the mesa tops to cliff alcoves toward the end of this period, and increased building activity in the alcoves began between A.D. 1230 and 1260. The resultant structures range in size from a single room to more than 200 rooms [3]. The alcoves sheltered Anasazi architecture from the elements, and the semiarid environment of southwestern Colorado further served to preserve this spectacular resource (see fig. 1).

Much Anasazi architecture is finished with mud plaster, especially the later sandstone and mud mortar cliff dwellings. It should be noted, however, that plaster was used to some extent by the Anasazi throughout their occupation of Mesa Verde. Nusbaum, for example, reported plaster in the earliest known Anasazi dwellings, pithouses, excavated in 1926 at Step House (Site # MV 1285) [4]. Until recently the focus of most plaster research has been on highly decorated plaster, rather than its systematic documentation or its potential relationship to cultural change and room function.

Nordenskiold, the first to scientifically document and record the archeological resources of Mesa Verde, recorded decorated plaster in several cliff dwellings during his 1891 exploration [5] (see fig. 2). Subsequent archeological work by Fewkes [6], Cattanach [7], Rohn [8] and others also provided some plaster data. In the Long House report (Site # MV 1200) Cattanach states:

> Some walls were "plastered" in places by smearing surplus mortar extruded between blocks and across the face of the surrounding wall. In most cases, however, the overall plaster was prepared and applied independently of the wall construction. The material was usually derived from the red and brown soils and was probably tinted more often than we realized with pigments made from hematite, kaolin and the like [9].

Rohn similarly describes Mug House plaster (Site # MV 1229), noting the consistent appearance of the pink plaster in the rooms. He hypothesizes that ". . . red loess from the mesa top continued in fashion for plastering after it had gone out of style as mortar . . .." [10]. While discussing kiva plaster, Rohn states that ". . . almost all the individual plaster consisted of a very thin brown or tan adobe body that had probably been acquired from Adobe Cave. Only in Kiva G was the reddish brown, mesa-top loess used instead. [11]"

Mud plaster is found in prehistoric sites throughout the American Southwest. It was not until Watson Smith's 1952 publication [12] that a relatively comprehensive survey of pueblo wall paintings became available. Smith's report included brief descriptions of plaster in notable sites throughout the Southwest, including Mesa Verde National Park. More importantly, the report includes an excellent description and analysis of decorative elements, materials comprising the mud plaster, and pigments used in prehistoric sites in the Jeddito Valley, Arizona.

It was not until the 1980s that there was a renewed interest in, and increased focus on, mud plaster. Reports by Chiari [13], Schwartzbaum [14], and others describing successful conservation treatments performed on decorated adobe surfaces became accessible to managers and resource specialists. Additionally, two reports by Constance Silver appeared, one in 1980 [15] and the other in 1982 [16]. Both publications used the extensive resources available through the International Center for the Restoration and Preservation of Cultural Property (ICCROM). These reports, more than any other publications, highlighted the lack of attention being given mud plaster and the need to pursue both the analysis and conservation of the prehistoric plasters in the American Southwest. Silver's reports graphically illustrated the need to develop comprehensive approaches to documenting and preserving both existing plaster and that being uncovered during current excavations. These two reports, combined with a certain amount of expanding professional interest in mud plaster, served to help increase general awareness that the plaster was indeed an integral component of Anasazi architecture and that its preservation was not ensured given present circumstances.

The pilot treatments described in the 1982 report involved the consolidation, reattachment, and cleaning of in situ plaster [17]. The report describes treatment methods and materials used in detail, and they will not be reiterated here. It should be noted, however, that this was the first time such treatments were tested on prehistoric mud plaster in the U.S. Mesa Verde National Park played an important role in the project since the treatments were performed in Kiva C and on the free-standing west exterior wall of room 28 in Mug House. The pilot treatment project also alerted park staff to the fragile nature of the plaster resource.

MESA VERDE PLASTER SURVEY

Park Management, becoming keenly aware of the lack of an integrated plaster data base and the continuing loss of this resource, obtained funding to begin a thorough plaster survey. Contracted survey work has been conducted during 1985 (Contract #-1490-4-0006) and 1987 (Contact #-1490-7-0002).

Major objectives, common to both survey projects, were:

1. to record the location and general condition of all extant plaster in selected archeological sites;

2. to compare generally, where documentation exists, the extant resource to that which was present historically; and

3. to provide recommendations for preservation treatment of the resource, keeping in mind the intimate relationships existing between the plaster and its masonry support.

A primary objective of the 1985 survey included a substantial archival work component. Mesa Verde National Park has accumulated a considerable amount of archival material since 1906. Most is located in distinct files in the Archeology Museum or at the Research Center. One major series of records pertains to ruin stabilization activities. The park's archeological ruins have undergone periodic stabilization since 1908. A second major archival data base is the archeological site record file. Other plaster data are located in historic photograph files and in the park's extensive archeological excavation records. All of these resources include substantial amounts of photographic and written plaster-related data.

These distinct data bases are not fully cross-referenced, nor are they automated. The idiosyncrasies of the records provided certain challenges to the contractor while integrating the plaster-related data. As mentioned previously, plaster has been addressed differently by past researchers. It may or may not have been specifically mentioned or reported in detail when archeological sites were surveyed and when excavation or stabilization work was documented. For example, older written stabilization records or completed archeological site forms may not have discussed the presence of plastered walls. However, photographs documenting the site or the work may clearly illustrate the presence of plaster. Also, when existing plaster was noted, the terminology describing or classifying it was not consistent. Decorated plaster may have been referenced using those terms or included under the grouping of "pictographs" as was done in the 1964 Wetherill Mesa survey report [18].

Nevertheless, the 1985 plaster survey contract successfully compiled and integrated much plaster data from the record groupings listed above. Eighty-five of the park's cliff dwellings [eighty-four are listed in the report] were reported as having documented prehistoric plaster [19] within as many as 1,861 architectural spaces. These data do not indicate the number of plastered walls, the extent of the plaster when documented, or the condition of the plaster. But, even when using these limited data, one can readily see that the cliff dwellings of Mesa Verde contain extensive and important mud plaster resources. How extensive, how important, and in what condition can only be determined through the examination of each architectural space in the eighty-five sites. Complete and systematic documentation of such an extensive resource is a time-consuming and expensive proposition. Obviously priorities must be established and a plan of action carefully formulated.

With the inception of the 1985 survey project, the contractor and park staff collaborated on the development of recording forms and formats. Each architectural space within certain cliff dwellings was to be fully documented, both in written and photographic form. It was decided to use a two-part, hierarchical survey form. One part generally documented individual architectural spaces. The second form was designed to document each wall containing plaster. Examples of these forms are available from the author. Data were recorded for each plaster's location, method of application, number of layers, presence of design elements, condition, color (Munsell), and extent. During the second survey minor revisions were made to this form, such as prompting for environmental and locational data pertinent to plaster preservation and for specific data concerning previous documentation and noted plaster deterioration [19]. However, data consistency was a primary objective of both surveys.

The plaster recording system used existing site maps and room numbering systems, and it was hierarchical by design. The system uniquely identifies each wall forming the plaster's immediate structural support, which is the basic recording unit. For example, MV 640-55-N denotes plaster on the north, interior wall of room 55, in site #MV 640. Similarly, MV 640-55-N-EXT identifies the same wall, but an exterior surface. The format and the system generally linked documented plaster walls to their spatial and functional contexts, served to systematize documentation while considering future automation of these data, and assisted in the analysis of structural concerns or ambient causes of deterioration [20].

Photographic documentation included at least one black-and-white photograph of each plastered surface. Additional photographs, black-and-white, color, or infrared were taken as needed to illustrate certain design elements and conditions. Each photograph was given a unique reference code on a photographer's log. Photographs also included the appropriate Kodak Scale and were referenced on plaster recordation forms. Drawings were made when needed to further illustrate complex or very poorly preserved motifs.

The 1985 survey established precedents for standardized plaster and condition terminology. Fully standardized masonry and architectural nomenclature has not been adopted by park staff. However, terms such as shaped or unshaped stone, single or double coursed walls, tower, kiva, and room were recorded during the plaster survey as they were used during previous archeological work in the park. The descriptive terminology for plaster and condition was kept to a useful minimum and was kept general. Further, each term was illustrated in final reports to facilitate their use and interpretation by future researchers. The glossary of terms used to document plaster, for example, included: aura incised design, painted design, incised and painted design, floor band, bichrome design, wainscot, colored wash, dado, de facto plaster, undecorated plaster, and absence of plaster [21].

The condition of the plaster was one factor evaluated when recommendations for further action were made by the surveyors. Terminology for specific examples of deterioration types and overall condition were established for both the surfaces and the plaster substrate. Surface deterioration caused by accretion (i.e., bird excrement, smoke blackening, nearby stabilization work, muddy runoff), and conditions such as powdering, flaking, separation from substrate and weathering losses were illustrated and defined. Along with the above surface condition nomenclature, several types of plaster deterioration were illustrated. These included lacuna, separation from walls, cracks, interlayer cleavage, and failing supports [22].

FIELD SURVEY RESULTS

The surveys documented plaster in eighteen sites containing just over one thousand architectural spaces. The cliff dwellings chosen for initial survey were the largest and best preserved. Preliminary data suggested that substantial amounts of plaster, both decorated and undecorated, were still present in all sites selected for documentation. Another factor influencing site selection was the interpretive importance of the site. Nearly all sites chosen for survey were open to public visitation or visible from public overlooks.

Over 1,900 square meters (20,500 sq. ft.) of plaster on 869 surfaces were documented during the surveys [23,24]. Approximately 75 percent of the plaster and the surface are in fair to poor condition. These figures certainly illustrate an extensive resource in need of attention. Numerous preservation-related recommendations resulted from the surveys. The more prevalent recommendations were:

1. to apply silicone beading to the ceiling of an alcove to form false driplines which divert water away from the buildings;

2. to stabilize architectural supports - often the base of a wall;

3. to closely monitor certain plasters;

4. and for a conservator to evaluate selected plaster for treatment.

It is not practical, nor is it feasible, to attempt to preserve all recorded plaster. A multicomponent action plan must be implemented if the plaster resource is to be documented and a significant sample preserved. A suggested action plan includes the following six major sections:

1. Active stabilization: Stabilize walls, control moisture to the extent possible, control rodents or birds, and eliminate insects - - continue developing a comprehensive approach to site preservation.

2. Monitoring: Develop a methodology and schedule to monitor systematically selected plaster based upon criteria such as overall condition, presence of design elements, uniqueness, representativeness of more mundane finishes (i.e., washes, monochrome or bichrome designs, auras, floor bands), interpretive importance, feasibility of preservation, and previous treatment.

3. Evaluation for conservation treatment: Backfill selected spaces, solicit conservation treatment proposals and contract for treatment, closely evaluate the effectiveness of the pilot treatments performed at Mug House.

4. Training: Further sensitize park staff (i.e. those responsible for management, interpretation, stabilization, and protection) to the importance and fragility of the plaster. Train the park's Stabilization Specialist and Ruins Stabilization Crew so that plaster monitoring, documentation, and preservation can be fully integrated into both the present stabilization program and future excavations, and ensure that newly recorded data are compatible with previous survey data.

5. Continue field surveys: Survey remaining cliff dwellings in priority order, again ensuring compatibility of new data with previous survey data, and improve survey methodology.

6. Expand research: Continue to support and formalize research projects related to plaster composition (pigments, binders, and minerals), material sources, plaster fabrication, determination of salts, and conservation treatment (cleaning, consolidation, and reattachment).

PLASTER ANALYSIS

Mud plaster from Anasazi sites has not undergone scientific analysis until relatively recently. Smith [25] reports the composition of kiva plaster from two sites in the Jeddito Valley as 90% sand and 10% clay. The report also lists thirteen colors and possible pigment sources, noting that it is unclear if pigments were added or if the clay and sandstone were previously stained. All pigments, except black, were apparently derived from inorganic materials. Smith also hypothesizes that an organic binding medium could have been mixed with pigments [26].

Recent studies by Silver [27] produced strikingly different and thought-provoking results. X-ray diffraction analysis shows that prehistoric plaster from Anasazi ruins in the four-corners area and a possible mud source in Mesa Verde National Park contain no mineralogical clays. Plaster from Lowry Ruin contains 75% quartz, 5-10% feldspar, 5-10% mica, and traces of additional material. The raw mud from Mesa Verde contains 50% quartz and 50% anorthite. The Lowry sample was also tested using stains specific to organic compounds. The plaster tested negatively, while a paint layer from Lowry tested positively for carbohydrates and proteins. The raw mud sample was not tested for organic materials. As suggested by Silver, the lack of mineralogical clay in her samples is remarkable, and the presence of organic binding media may partially account for the cohesiveness and durability of the paint layers and plaster.

Mesa Verde plaster samples were recently examined by Dr. Mary Griffitts [28,29]. X-ray diffraction of kiva and room plaster samples from Step House and Mug House demonstrate a departure from both Smith's and Silver's data. Table I illustrates comparative sample data from Silver's and Griffitts' reports. Of particular note is the relatively low percentage of quartz and high percentage of calcite in the white plaster from both Mesa Verde sites analyzed by Griffitts. Additionally, measurable percentages of mineralogical clay are present in the Mesa Verde samples.

Table I. Comparative Results of X-Ray Diffraction (After Silver 1987 and Griffitts 1989,1990) - - Note: Totals may not equal 100% due to sample variability.

Site/Sample	Quartz	Calcite	Feldspar	Kaolinite	Gypsum	Mica
Lowry Ruin	75%	-	5-10%			5-10%
River House Ruin	80%	Tr	15-20%			
MVNP - Raw Mud	50%		50%			
Mesa Verde National Park Plaster Sample Data Follows:						
Step House - Kiva A - dark	93-95%	0-10%	10-15%	2-3%	1-2%	1%
Step House - Kiva A - white	37%	15%	17%	2%		
Mug House - Rm 28, ext-white	43%	30%	8%	1%	2%	1%
Mug House - Rm 28, ext-pink	72%	4%	8	3%	2%	2%
Mug House - Kiva C	90%	15-20%		5%		

While examining thin sections from Mesa Verde plaster Griffitts identified serecite, a very finely divided mica resulting from the weathering of feldspar. Serecite is not found in any of the geologic formations studied by Griffitts. It is present, however, in the lower zones of the park's loess soils, just above an underlying layer of caliche. The X-ray diffraction data and occurrence of serecite suggests that loess soils may have been combined with caliche (calcite) to create certain plasters. Caliche evidently is a major component of the white plaster samples subjected to the above analytical tests. An empirical experiment by Griffitts produced a good plaster (50% caliche and 50% loess) of similar color and appearance to some original Cliff Palace plaster. The Mesa Verde plasters have not been analyzed for the presence of organic binders. This should be done in the future. With such tests one must be certain the samples have not been contaminated by previous conservation treatments or altered during burial. It would also be interesting to test hypothesized source material for the presence of organic material as a control, to ensure the raw materials do not contain substances which might skew the analysis.

CONCLUSION

Mud plaster in archeological sites of the American Southwest has not received the attention it warrants or needs. The plaster survey program at Mesa Verde National Park is unprecedented in scope, with over one thousand architectural spaces inventoried and over 1,900 square meters (20,500 sq. ft.) of plaster documented. Surveying, locating, and recording plaster and documenting its condition are necessarily the first steps in a comprehensive plaster resource preservation program. The Mesa Verde survey project illustrates the importance of such inventory data and the extent of the plaster resource in that park. It also illustrates the need to establish preservation priorities and a multi-faceted action plan since it is not feasible or practical to conserve all plaster. A suggested action plan includes stabilization, monitoring, evaluation of treatment needs, training, continued survey, and expanded research programs. Such programs are not only applicable to Mesa Verde, but also to all other areas with the potential for prehistoric plaster among their resources.

Silver's 1987 study discussing the presence of organic binding media and the absence of mineralogical clay in certain Anasazi plaster is intriguing. Similarly, the high calcite content, presence of mineralogical clays, and the presence of serecite in samples of Anasazi plaster from Mesa Verde is also interesting. Only a few samples comprise the present data base and more samples must be analyzed. Additional research in the areas of plaster composition, pigments, conservation treatments, and plaster replication is needed. This basic research must be performed if we are to reconcile apparently discordant data and to continue making progress with actual conservation treatments and ensure the long-term preservation of Anasazi plaster.

With further refinements in our ability to identify the composition of prehistoric plaster and material sources, plaster may prove to be a useful cultural and temporal indicator. Anasazi masonry styles have been used to illustrate certain attributes characterizing developmental phases by which sites are classified [30]. Regional variations in masonry style have also been used to identify sites attributed to different branches of the Anasazi [31,32]. The architectural finishes (i.e., plaster and paints) applied to the masonry potentially have similar capabilities.

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ACKNOWLEDGEMENTS

Financial support for this project was supplied by the Horace Albright Employee Development Fund. The research was conducted while I was Regional Curator, Rocky Mountain Region, and it could not have been concluded without the support of the Division of Cultural Resources. Special thanks are due to Dr. Mary Griffitts for her timely research and gracious assistance. The staff of the Mesa Verde National Park Research Center was extremely helpful, providing photographs, reports, and work space. Thanks are also due to Margo Surovik Bohnert for her support and patience and to Dr. Ann Johnson for her editorial assistance. I remain responsible for all errors and omissions.

Figure 1. 1891 photograph of Square Tower House.

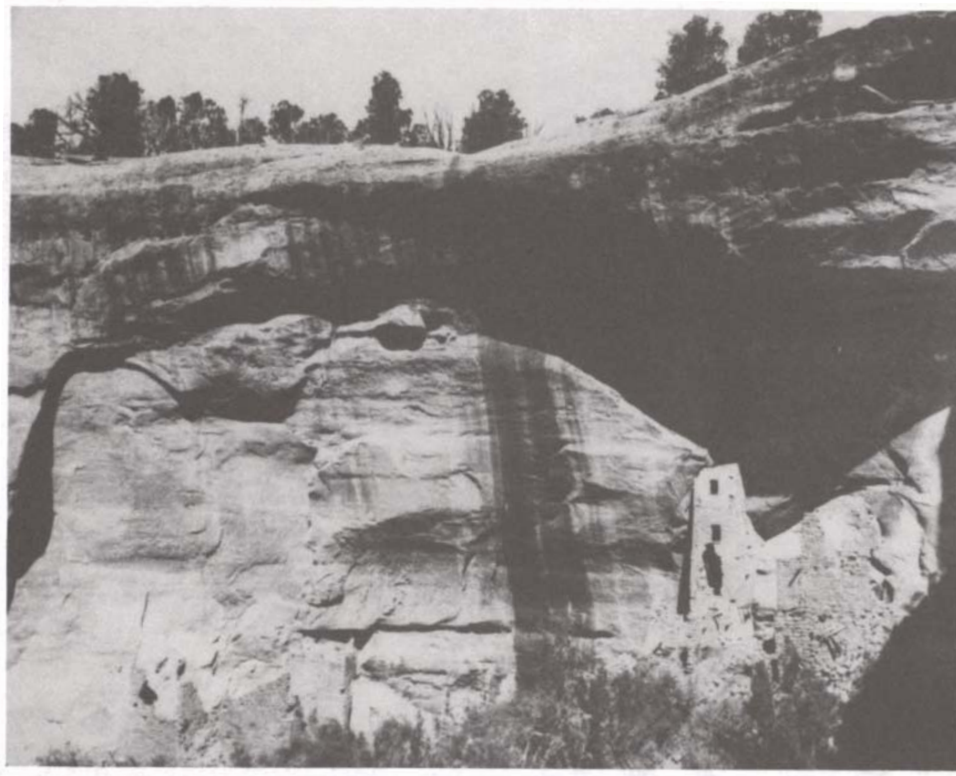

Figure 2. 1891 photograph of Square Tower House, by G. Nordenskiold.

ABSTRACT

Among the various techniques of earthen architecture preservation which have been applied in the past, the consolidation of vertical surfaces by chemical agents and the capping of the top part of walls play an important role. The ideal characteristics of a good consolidant are outlined. The consolidation mechanisms of synthetic resins and ethyl silicate are discussed, together with their advantages and disadvantages. The performance of field treatments with ethyl silicate and of capping techniques after twenty years of application are evaluated for a case study in Iraq. A way to regain good adhesion on deteriorated surfaces, based on the application of rice paper (moistened and pressured) is described.

KEYWORDS

Adobe, Earthen Architecture, Consolidation, Ethyl Silicate, Synthetic resins, Capping, Long-term evaluation.

CHEMICAL SURFACE TREATMENTS AND CAPPING TECHNIQUES OF EARTHEN STRUCTURES: A LONG-TERM EVALUATION.

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Introduction

The idea of solving the problem of adobe preservation by coating the surface with some perfect consolidant should be dismissed. Each preservative shows advantages and disadvantages; the perfect treatment has not yet been discovered and probably never will be. Adobe is a weak material that has always been used with the idea of constant maintenance and repair. In most cases the walls were originally protected by roofs, which in archaeological excavations are missing. One cannot expect to stop the natural evolution and modification of the material. All we can hope to do is to reduce the speed of deterioration.

Chemical surface treatments

An ideal consolidant for adobe should have the following characteristics: 1) confer water resistance but not water repellency in order to allow water migration both in liquid and vapour phase; 2) leave pores and capillaries open, and allow for other impregnations, even with different products; 3) confer mechanical strength and abrasive resistance both in dry and wet conditions; 4) have good penetration, i.e., low viscosity; 5) should not form films on the surface, nor show an abrupt planar boundary with respect to the untreated core; 6) have a thermal expansion coefficient similar to that of adobe; 7) should not change the colour, or cause gloss; 8) be resistant to stresses caused by salt crystallization, capillary rise of ground water, and freeze-thaw cycles; 9) be durable, i.e., resistant to water, and photo-oxidation; 10) be easily applicable, possibly also in damp conditions, and cheap; 11) should not be harmful to the operators; 12) should be reversible, if possible (see also [1]).

It is my opinion that a product fulfilling all these characteristics does not exist.

The consolidants most used on adobe are synthetic resins, usually thermoplastic, and ethoxysilanes. It is important to underline that general statements on the behaviour of whole classes of compounds have almost no meaning. Products that have the same nominal composition may vary greatly from one producer to another; also the application technique could influence the final results. Each individual product should, therefore, be tested on the specific material, possibly with accelerated aging tests, wet-dry cycles, and salts crystallization. Even this cannot assure that a consolidant which has given good results in the laboratory would behave equally well on the long-term field application. Large field comparative tests are presently carried out on specially built walls at Fort Selden (New Mexico State Monuments) and in Grenoble (CRATerre) for various products and cappings. The results of these tests will be extremely valuable to identify suitable consolidants. Keeping this in mind, one can try to describe the consolidation mechanism and to evaluate advantages and disadvantages of both types of consolidants.

Synthetic resins

Synthetic resins are long chains of organic polymers derived from a vast range of monomers. The most commonly used are the polyvinyl acetates, acrylics (among them Acriloid B72 and Primal AC33) and polyisocyanates [1]. They can be used in solution in organic solvents or in water emulsions, or the polymerization can be obtained in situ by the use of catalysts or by reaction with atmospheric moisture.

Solutions are best suited for surface consolidation, because the products are pure, and they show good aging properties and penetration.

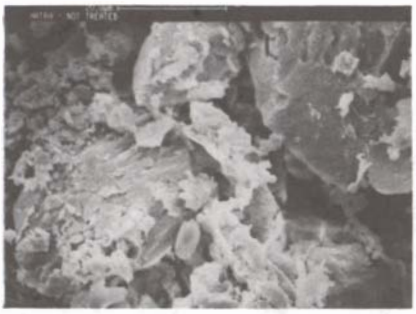


Figure 1. Scanning Electron Microscope (SEM) image of a nontreated sample from Hatra.

Water emulsions are obtained by addition of surfactants (usually soap-like substances). These additives may increase the speed of deterioration of the resin, by oxidation, breaking of the polymer chain, and cross-linking between chains. The results are change in colour, brittleness, and break down of mechanical properties. These mechanisms require the action of light (especially UV-radiation) and oxygen. In the case of emulsions the polymer globules suspended in water are relatively large, the liquid has a high viscosity, and penetration is low. Water is not a good carrier in the case of adobe, since it causes swelling of the clay particles and decreases the mechanical properties with the risk of material detachment during the treatment. Emulsions should therefore be applied as adhesives only, by injection inside the walls, and never on the surface.

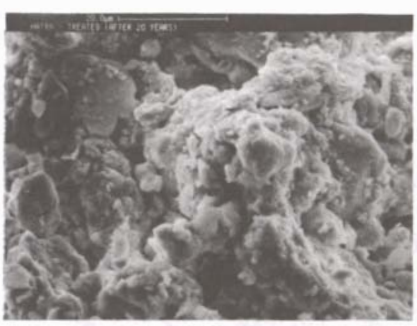


Figure 2. SEM image of a sample taken from the wall treated with ethyl silicate in Hatra. Although there is very little difference between the two "landscapes", the consolidated part is water resistant.

Synthetic resins act as consolidants by penetrating inside the pores and coating the loose particles. Chemical reaction normally does not take place between the polymer and the material. The strengthening is obtained by the setting of the resin at the moment in which the solvent evaporates. In many cases, reverse migration of the polymer to the surface, as the solvent (especially if highly volatile) evaporates, causes the formation of a thin film. If the coating is not porous, which is the case for most synthetic resins, and does not allow for water transport, both in the liquid and vapour phase, the water that can gain access beneath the protective layer causes stress and detachment. Most synthetic resins have high thermal expansion coefficients, of one order of magnitude larger than adobe. Since the surface tends to be warmer than the inside during the day, and colder during the night, stress is developed at the interface, with possible detachment. Among the advantages of synthetic resins one can quote: good mechanical properties, a certain degree of reversibility with non-crosslinking types, and the fact that they may act as adhesives as well.

Technical description of the ethyl silicate reaction with earthen material

Ethyl silicate (tetraethoxysilane) is partly inorganic and partly organic, but after complete curing (which may take a long time) it leaves a purely inorganic residue. There are several kinds of commercial products (see the Materials section). The monomer consists of a silicon atom to which four ethoxy groups are bonded, $Si(OCH_2CH_3)_4$. When a water molecule reacts with an alcoholic residue, hydrolysis takes place: one ethyl alcohol molecule is formed (which evaporates) and an acidic residue remains attached to the silicon atom to form Si-OH.

The hydrolysis reaction is the following:

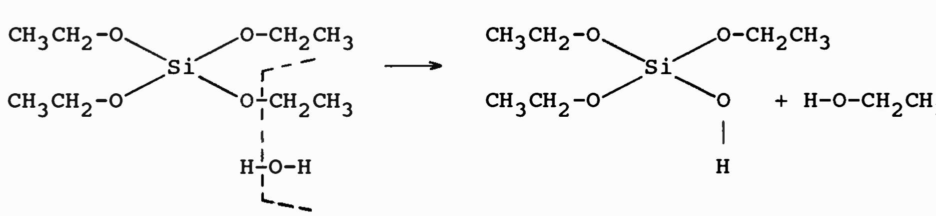


Figure 3. Application of moistened rice paper: the pressure allows adhesion to be reestablished.

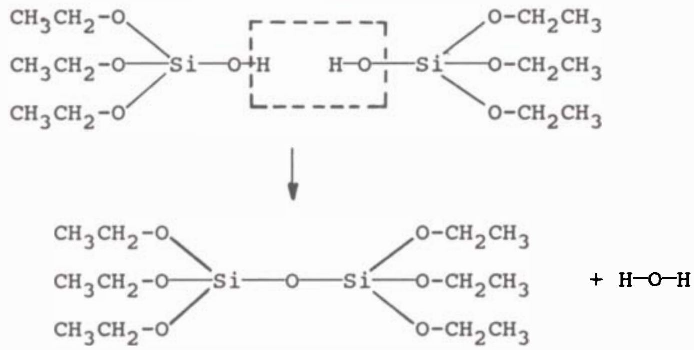
Figure 4. Detachment of the paper without any loss of surface material.

Figure 5. Overall view of the capping with one layer of strengthened bricks at Tell 'Umar, showing the plant overgrowth.

Figure 6. A section of the covering with one layer of strengthened bricks, still in perfect condition. (Tell 'Umar).

The hydrolysis of the four groups can take place at different times. If the four alcoholic residues are all hydrolyzed, silicic acid is formed: $Si(OH)_4$. When two acidic groups belonging to different molecules interact, condensation or polymerization takes place. One water molecule is released (and is again available for the hydrolysis reaction) and a strong Si-O-Si bond is formed.

The condensation reaction is the following:



A small amount of acid acts as a catalyst for hydrolysis. In the application to adobe, there is no need to increase the speed of the reaction, and better results are obtained without addition of acid [2-4]. With polymerization, a three-dimensional network of silica tetrahedra sharing one vertex is formed. Some of them usually still have ethoxy groups attached to the Si atom. The clay particles abundant in adobe have a large number of hydroxyl groups (-OH) located on their surface. Condensation may occur between the acidic group of the silica framework and the hydroxyls of clay particles. Of course, an extremely large number of such bonds are formed, and, if the clay particles are sufficiently close to one another, the silica framework helps to keep them together.

One of the major causes of deterioration of adobe is water, which separates the clay particles constituting the binding agent of the bricks. On excessive wetting eventually the clay is dispersed in a water suspension. The ethyl silicate treatment, by adding strong bonds between the clay, prevents clay platelets from being separated by water, and therefore gives the material the necessary water resistance. For the first period after treatment, silica gel is formed inside the pores and the total porosity is reduced. While the polymerization continues, the silica gel contracts and the pores reopen. With time, very little material remains inside the adobe, even the micro-pores are almost completely open, but the clay particles are still bonded together. The overall effect of the treatment is to confer water resistance to the material but not water repellency, neither at vapor nor liquid level [5].

Figure 1 shows a scanning electron microscope (SEM) picture of an untreated sample from Hatra, while Figure 2 shows a treated one. It can be seen that the changes due to the treatment are hardly detectable.

The treatment is completely irreversible, violating the principle that every intervention in conservation should be totally reversible. The fact that not only the surface and appearance of the material, but also its intimate structure, undergoes so little modification may in part justify the irreversibility. Other consolidants, even totally different in nature, can easily be applied, since the porosity and polarity of the material are practically unchanged.

The application by spraying makes its use very easy and has the advantage of obtaining a larger penetration in those parts which are more porous than others, thus leaving a very irregular separation between the treated and untreated parts. This strongly reduces the chance of detachment of the strengthened layer. Cleaning of the surface and extraction of soluble salts can be done after consolidation. This is not possible if synthetic resins are used.

Figure 7. On the north side, the unprotected wall has suffered an enormous loss of material, due to the rain. (Tell 'Umar).

Among the disadvantages, beside its irreversibility, one can recall that the treatment cannot be applied to wet surfaces. In this case, the excess of water causes the hydrolysis reaction to take place at much higher speed than polymerization. A glossy, fragile crust is formed, which crumbles without making the desired connections with the clay particles. Synthetic resins also present application problems to wet surfaces.

Another disadvantage is that ethyl silicate is not an adhesive, but only a consolidant. If a gap already exists between two blocks of adobe, they will be individually consolidated but not "glued" together. To achieve adhesion between already separated parts, one should make use of other strategies: the most obvious is to intervene as soon as possible, ideally during excavation, in order to have surfaces that are not yet damaged by weathering. If the surface is already damaged it is possible to regain adhesion by remodeling the surface using rice paper, water and pressure. The paper allows the crust to be sustained while it is carefully moistened. The material becomes slightly plastic, and, by exercising pressure with a hard sponge, one can reestablish an acceptable degree of adhesion. When almost dry, the paper can be detached without any loss of material, including pigments (See fig. 3,4). Both of these strategies were applied with success in the conservation of a painted frieze in Cardal, Peru, in 1987 (unpublished). If the detached crust is thicker than a few millimeters, the risk of it falling during the application of the rice paper is too high. Injections of synthetic resins (water emulsions) in the interior of the wall are recommended in this case.

Figure 8. The canalization of rain water over Tell 'Umar. In spite of some plant growth and some minor damage, this drainage system worked properly.

Preservation of sites in Iraq: a case study

In 1968 a preliminary campaign for the conservation and preservation of archaeological finds in unbaked earth was carried out in Iraq, with the aim of documenting the problem of mud-brick deterioration [6,7]. Various laboratory tests of surface protection were performed, using most of the products widely used at the time. Ethyl silicate seemed to give the best preliminary results and was selected for major field tests, done in the Seleucia area and in Hatra in 1969. Synthetic resins (polyvinyl acetates and acrylics) were also used on a minor scale, by injection.

One liter of Silester ZNS, three liters of ethyl alcohol (96°), and 1 ml of hydrochloric acid as a catalyst was used to treat 1 m^2. The penetration was 2-3 cm in depth, and after a day or two the wall reassumed its previous colour. No changes in appearance were observed, but the water resistance was greatly enhanced. After a month of spraying water on selected spots three times a day, there was no evidence of erosion, while on a nearby untreated part a hole was formed after the first three sprayings.

Figure 9. A natural canalization of water, left unprotected, to be compared to Fig. 8 (Tell 'Umar).

Capping of the top part of walls

The yearly average rainfall in the area is about 300 mm, concentrated in a few torrential storms. Furthermore, in some sections people had to walk on top of the walls. For these reasons, it was decided that the chemical surface protection alone would not be sufficient, and two capping techniques were tried. The first one, used in the "Archives" of Seleucia, consisted of a layer of a few cm formed with a mix of earth and sand, with the addition of a minimum amount (5-8%) of portland cement, to avoid an excessive

Figure 10. A view of the "Archives" in Seleucia. The top of the walls was capped with soil-cement, which did not prove to be effective, since there was formation of water pools at the bases of the walls.

hardness. This capping was applied in two layers on the moistened surface. After good compression and drying of the first layer, the few unavoidable cracks were sealed by a second, thinner layer made with a mixture less rich in water. For a few days straw mats slightly sprinkled with water covered the capping to avoid an excessively quick drying process. With this procedure the cracking of the surface was practically avoided.

Trials of capping with addition of asphalt were also attempted, but immediately proved to be disastrous, perhaps because of the poor homogeneity of the slurry, which was mixed by hand.

A second type of capping was used to cover a large section of a wall, at Tell 'Umar. It consisted of a single layer of new stabilized bricks, made with the same soil-cement mix with the addition of straw. This allowed for a proper drainage system for the water that ran down from the artificial hill. A large quantity of bricks was manufactured using wooden molds. They were well dried in the sun for over a month, covered with wet straw mats for the first week and turned over every three days. The resulting bricks were perfectly solid, without any cracks.

Evaluation of the results

All the work in Iraq was done mainly in 1969. In the spring of 1971, the ethyl silicate treatments were still in perfect condition, and it was easy to notice the difference between the treated and untreated parts, which had already severely suffered from rain. The capping with soil cement showed some cracks, and in a few parts water infiltration had eroded preferential channels. The new layer of bricks was perfectly preserved with the exception of the vertical walls at the end of the drainage system which, being immersed in water, had collapsed. At that time, some repairs were made. After this, no maintenance work at all was done to the site, which was abandoned.

Figure 11. Another view of a small room in the "Archives".

The present situation, after twenty years

In May 1989 a critical evaluation of the work was done. The capping with one layer of straightened bricks gave the best results (see figs. 5,6). The canal that was devised to disperse the water proved to be effective (see figs. 7,8,9). At one point the water found a different path, and a lot of damage occurred. It would have been easily avoided if the site had been maintained.

The necessity of maintenance can never be stressed enough.

Figure 12. Detail of the soil-cement capping, partially detached and cracked. Besides damage due to temperature changes and water infiltration, it should be remembered that people walked on the capping.

Some of the vertical walls were broken by the pressure of the roots and trunks of trees. On the north side, where the new bricks were not put in place, erosion due to water caused the loss of large mass of earth (see fig. 7).

Overall, the technique of putting one layer of new bricks on top of the walls can be judged in a very positive way. Of course, the original material is no longer visible, but all archaeological and architectural information is still retrievable from direct inspection. This sacrificial layer can easily be removed in case more excavation is needed. This technique should not be confused, by any means, with large reconstruction of walls that are quite often carried out even using baked bricks set on top of small remains of adobe walls. This type of intervention should never be done.

The general condition of the Archives was disappointing (see figs. 10,11). Most of the small rooms were filled with earth, in part fallen from the walls, in part carried in by the wind. In some parts the capping had resisted, while in other parts it was cracked, allowing water infiltrations (See fig. 12). This confirms the opinion [8,9], that in the case of small rooms located below the field level, without drainage and with the possibility of water pool formation at the base of the walls, the only possible intervention is complete, immediate backfilling.

To check if the capping reduced in any way the speed of deterioration, a comparison was done with the nearby excavation of "Via Porticata", which had undergone the same abandonment for twenty years. Most of the walls completely disappeared, with the exception of two rooms, capped with soil cement (see figs. 13,14).

Figure 13. Rooms at "Via Porticata", in the Seleucia area, without any conservation work.

It can be concluded that the endurance of walls can be enhanced, to a certain extent, by soil-cement capping, provided that the bases of the walls are not in direct contact with water. It should be noted, however, that constant maintenance is needed, which seldom can be ensured. Furthermore, since the weakest point is the connection between the capping and the original vertical surface, capping the top part of a wall has some meaning only if the vertical surfaces are consolidated as well. In any other case, the capping is almost ineffective.

The ethyl silicate treatments done at the Archives were not visible, since most of the walls were covered with debris. After excavation the consolidated part was not relocated. The moisture and salt content were extremely high, and the very next day the entire surface of the excavation was covered with white salt efflorescences. The water table level was less than a meter deep. Unfortunately there is not enough documentation to establish when and why the treatment failed. What can be said is that under drastic conditions - e.g., when a wall is impregnated with salt water for twenty years - the consolidation with ethyl silicate is not effective enough to protect it.

Figure 14. Two rooms at "Via Porticata" which were protected with the soil-cement capping. In this case the capping performed better, probably because people did not walk over it.

In Hatra environmental conditions are different from Seleucia. The rainfall is more or less the same, but the water table is much lower. The treated wall had a stone base and did not collapse. The effect of rain alone on treated and untreated parts can be seen. One row of bricks at the top was left untreated for comparison. Figures 15 and 16 show that clay from the top row was washed down and covered the treated bricks. This clay encrustation was easily removed by the use of a rough brush, without effecting the consolidated surface. Even very fine details (see figs. 17,18) were perfectly preserved.

It can be concluded that in this case (as in many other similar ones, for example in Chan Chan, Peru) the ethyl silicate treatment did confer enough strength to the surface to counteract the effect of rain for twenty years.

General conclusions

Of the various conservation measures undertaken in Iraq twenty years ago, some endured this long period of abandonment remarkably well, and some did not.

Among the positive interventions one can note: a) the covering of the top of walls with a sacrificial layer of one row of new bricks; b) the repairs of already damaged walls by the use of the same kind of bricks, when well anchored to the original part; c) the water disposal obtained by the canalization of rainfall using ad hoc designed paths made with the strengthened bricks; d) the surface treatment of vertical walls with ethyl silicate, provided that the bases of the walls are not damaged by water.

Even small faults in the execution of this kind of work can

Figure 15. Wall treated with ethyl silicate in Hatra, as it appeared in 1969. The top layer of bricks was not consolidated.

Figure 16. View of the same wall in 1989. The bricks on the top are washed away from the rain, and the material ran over the lower, consolidated part.

Figure 17. Detail of the same wall in 1969.

Figure 18. Same detail after partial cleaning with a harsh brush (see especially the white gypsum mortar). Even small details are well preserved.

result in serious damage. It seems advisable, therefore, to re-evaluate the interventions after a period of time, correcting the possible mistakes. It should be stressed that a regular maintenance program is of paramount importance.

Among the failures is the capping done with a thin layer of strengthened soil directly on top of walls. Although it produced some results, it was not sufficient to preserve the walls for such a long period, especially under the very harsh conditions at Seleucia Archives. The formation of water pools at the bases of walls remains the biggest problem.

The ethyl silicate treatment on surfaces of walls severely affected by salt water also seems not to be a strong enough protection.

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Materials

SILESTER ZNS: ethyl silicate partially condensed (about 10 molecules of monomer), produced by MONSANTO (USA). Dealer: Pietro Carini, Via S. Marta 23, Milano (Italy) Tel. 06-874477.

TEOS: tetraethyl-ortho silicate, produced by Union Carbide Corporation. 270 Park Avenue. New York 10017 (USA).

Wacker Strengthener OH: Ethyl silicate mixed with solvent (toluene) and catalyst, produced by Wacker-Chemie GmbH, Prinzregentenstrasse 22, Munchen (FRG).

SYNTHETIC LATEX-SOIL SLURRY, A NEW ADOBE PRESERVATION TECHNIQUE

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ABSTRACT

The problems of unnatural appearance and poor adhesion usually encountered when synthetic latexes or latex plasters are applied to adobe are overcome by use of a latex-soil slurry applied as a thin coating. The key property of these coatings is the ability to prevent the passage of liquid water while allowing the escape of vapor water from the interior of the structure. Due to the high fluidity of the slurry, application can be made a simple brushing operation.

KEYWORDS

Adobe, latex, soil-slurry, stabilization, erosion protection.

Background

A wide variety of polymers and polymerizable monomers have been evaluated in the preservation and restoration of earthen or stone structures and artifacts [1]. Most of these are applied as penetrating solutions or sprays. Synthetic latexes (aqueous polymer emulsions or dispersions) have been used for such work only to a limited extent, mainly as binders for plasters or mortars. Typical examples are Fenn's work at Fort Bowie [2] and Bent's Old Fort [3].

The author has investigated the application of latexes to soils for a number of years in both laboratory and outdoor exposure tests that have clearly indicated the benefits and problems presented by these materials. Latexes, like most aqueous treatments, penetrate very slowly and darken the surface; moreover heavy applications give an unnatural glossy appearance. On the other hand, latexes are easy to work with and clean up, and some have excellent mechanical properties and resistance to degradation. These properties depend on the structure of the polymer and also on the type of emulsifier used in making the latex. The emulsifier greatly affects the degree of wetting and spreading of the polymer spheres in the latex on the soil particles. The relationship between the electrical charge of emulsion particles and that of mineral surfaces referred to by Clifton [4] has been found to be too simplistic to allow a narrow definition of the best emulsifiers. Many of the latex emulsifiers are nonionics.

The author has evaluated a large number of synthetic polymer latex commercial products and found only three or four so far that are suitable for adobe preservation/restoration work. These are Airflex (R) 500 and 510, an ethylene-vinyl acetate copolymer; UCAR (R) 365, a vinyl-acrylic copolymer; and possibly Rhoplex (R) E-330, an acrylic resin emulsion, which was promising in some initial testing. The field testing was all done with Airflex 510 or UCAR 365.

Latex used as a binder for plaster does not usually cause a color change problem if soil identical or very similar to the substrate is used. Sometimes soil eroded from the structure to be treated can be used. Latex-soil plasters tend to have a short useful life due to adhesion failure. This is because most plasters are fairly thick, 0.5 cm or more, and are usually mixed with latex contents of 5% or more based on the weight of dry soil used. Note that most latexes contain 45% to 55% by weight of active polymer. The combination of thickness and high polymer content can make a moisture barrier that will allow the accumulation of water at the interface between the wall and the plaster. Both additional damage to the interior and loss of the plaster will result in time. This problem has been described in detail by Clifton [5] who points out that restoration work on adobe by indiscriminate application of preservation materials can cause more damage than benefit.

A New Approach: Latex-Soil Slurry

In an attempt to balance the benefits of polymer-containing coatings and plasters against the problems they may create, the use of thin coats of latex-soil mixtures of slurry consistency was investigated. Field tests on adobe test walls did not develop any of the problems described above and were very effective in preventing erosion for four years of San Francisco Bay area weather. These coatings function by shutting out liquid water, but allowing vapor water to escape from the interior, and thus prevent interior condensation. Key features are the liquidity provided by adding sufficient water to the coating mixture to give a slurry and thus allow a thin application, and a reduced amount of latex, 0.5% to 3.0% (as supplied) based on the dry weight of the soil in the mix. The cured coatings were about 1.5 to 3 mm thick.

Application Technique

The consistency of the latex-soil slurry is regulated by the water content and does not appear to be critical. The amount of water to be used is determined by making trial mixes with the test soil and generally is about 17% to 20% of the weight of dry soil. The optimum amount of latex will probably be about 1.0% to 1.5% of the dry soil weight, but should be confirmed by making several small scale applications with slurries containing a range of latex concentrations. The test slurries are applied to a suitable substrate, allowed to cure for several days of dry weather, and then evaluated for erosion resistance. Rubbing the wet test surface with the finger should not result in a loss of soil after moistening with a water spray. The minimum amount of latex that gives satisfactory erosion resistance should be used. The latex should be first mixed with the total amount of water to be used to ensure a uniform coating. An ordinary paint brush works well as a slurry applicator. A gunite-type sprayer could probably be used for a large project. The slurry should be mixed occasionally, but settling does not appear to be a problem. The slurry can also be stored in a closed container and remixed again before use.

The substrate should be in sound condition prior to slurry application. Loose material should be removed by brushing if not too deep or extensive. Reinforcement of the surface prior to slurry application can be accomplished by a light treatment with a penetrating resin solution. The application rate must not be so heavy that it will form a water vapor barrier. Acryloid F-10 (R), a 40% solution of butyl acrylate in an aromatic naphtha, applied as a 10% solution in xylene works well. Acryloid F-10 has excellent weathering properties, but darkens the soil surface to an extent that it would probably not give an acceptable appearance without a latex-soil slurry overcoat.

The application of latex-soil slurry will not prevent the wicking up of ground moisture into the lower layers of the an adobe structure. In some cases the injection of a chemical grout or insertion of a metal barrier plate at ground level, as suggested by Clifton and Davis [6], may be considered.

Field Evaluations

All tests were made on walls constructed of unstabilized adobe bricks and plain soil mortar obtained from the Hans Sumpf Adobe Company of Madera, California. This adobe soil is considered an ideal soil for brick making. The composition is shown in Table I. These unstabilized bricks were made in a special plant run during which the usual asphalt emulsion stabilizer was withheld.

The test walls were constructed and coated in the fall of 1982 in the San Francisco Bay area. Four of the walls were about 1.5 m wide and 1 m high. The fifth wall was 3 m long and 1 m high. Soil slurry compositions ranged from 1.5% to 3% latex (as supplied) based on the dry soil weight. Only the Airflex 510 (R) and UCAR 365 (R) latexes were used. Application of the slurries was made with an ordinary paint brush. The coatings had a thickness of about 1.5 to 3 mm. Plaster of the same composition was troweled on one of the short walls and on the long wall. Some of the wall areas were given a light spray of a 10% solution of Acryloid F-10 (R) in xylene one day prior to the slurry appplication.

Inspections were made at intervals until January 1986 when shortly thereafter the four short walls were demolished to make room for another project. The fifth longer wall still stands today and continues to be used for new experimental work. At the last inspection in 1986 a heavy rain was falling making it possible to evaluate color and surface hardness under wet conditions. All applications, except the heavier plaster application, were in excellent condition. The thick plaster had serious adhesion failures. Otherwise no differences were observed between the two latexes or their concentrations. All surfaces when wet had the usual dark color of wet soil; they all returned to the normal soil color when dry. When the surfaces were pressed with a blunt rod, the areas sprayed with Acryloid F-10 (R) prior to slurry application had greater resistance to indentation than the corresponding untreated areas.

The longer wall which had been coated with a heavy latex-soil plaster developed serious adhesion problems and damage to the interior core. It has since been repaired and is being used to study other restoration methods.

Conclusions

Application of latex-soil coatings as a fluid slurry is a promising method for preserving and restoring adobe structures. However, since all field testing has been conducted with only a single soil type and outdoor exposures have been limited to only several years, the method should be regarded as experimental until tested more extensively. Thin application and use of minimum latex content in order to avoid formation of a water vapor barrier prevent wind and water erosion without damaging the core soil structure. The slurry is easy to apply and should be lower in cost than many preservation techniques. The method should also find application for earth housing improvement in developing countries as well as for the preservation of historical structures.

Table I

Composition of Hans Sumpf Company Adobe Soil

Particle Size Analysis

By wet sieve:

Grain size, mm	% Finer, by weight
2.30	99.9
1.00	95
0.59	83
0.30	64
0.20	56
0.15	52
0.08	45

By Coulter Counter (R):

On fraction below 0.08 mm grain size

Mean grain diameter: 7.3 μm

5% by volume is greater than 27 μm

95% by volume is greater than 2.0 μm

Clay Types: Kaolinite and clorite: 15%-20%

Bentonite: Nil

Materials List

Airflex 510 (R), Aqueous emulsion of ethylene and vinyl acetate copolymer, 55% solids, Air Products & Chemicals, Inc., Box 535, Allentown, PA 18105. Telephone: (800) 345-3148.

UCAR 365 (R), Aqueous emulsion of vinyl-acrylic copolymer, 55% solids, Union Carbide Corporation, 39 Old Ridgebury Road, Danbury, CT 06817-0001. Telephone: (203) 794-6300.

Acryloid F-10, Butyl methacrylate polymer, 40% solution in VMP naphtha, Rohm and Hass Company, Independence Mall W., Philadelphia, PA 19105. Telephone: (215) 592-3000.

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DETERIORATION AND CONSERVATION OF SOME MUD BRICK IN EGYPT

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ABSTRACT

Mud brick from two archaelogical sites at Abu-Sir and Mataria in Egypt was studied by X-ray diffraction, atomic absorption, thin section analysis, and scanning electron microscope. X-ray diffraction data showed that it consists of the following minerals : quartz, plagioclase and potash feldspars, mica, and variable amount of clay minerals. Deterioration phenomena are due to chemical weathering by water and effect of salt. Consolidation of mud brick was carried out by applying tetraethoxysilane, methyltrimethoxy silane, and methylmethacrylate-butylacrylate copolymer. Results were examined by scanning electron microscope.

KEYWORDS

MUD BRICK, DETERIORATION, CONSOLIDATION, WEATHERING, X-RAY DIFFRACTION, PETROGRAPHY.

1. INTRODUCTION

Mud brick has been widely used in ancient Egypt since the predynastic period in Naqqada, Upper Egypt. It was commonly used in constructing tombs in the 1st and 2nd Dynasties at Saqqara and Aby-dous. Clay was abundant all over Egypt, so houses were built from mud bricks which were suitable to the dry climate of Egypt. The size of the ancient Egyptian mud brick varied, some had the same dimensions as the recent ones, while others were very large size. In the Egyptian museum, there are two ancient mud brick with dimensions 96.5 x 53.3 x 30.5 cm. As stone became known, tombs and temples were constructed from it, whereas houses and pharaonic palaces were still built from mud brick both for poor people and for nobles. This is the reason that most of ancient Egyptian houses and palaces have vanished, because mud brick is less durable than stone used for tombs and temples [1].

Mud brick is composed of sand, silt, clay, and fibrous organic materials such as straw may also be added. Sand was added to increase compressive strength and minimize cracking when the adobe dried. Non-clay minerals act as internal binder. They reduce contraction and prevent cracking [2].

At excavation sites in Abu-Sir and Mataria, it was found that mud brick structures were very friable and extensively deteriorated. The aim of the present work is to study the deterioration factors of adobe. in these two sites and to find out the suitable consolidants for their conservation.

2. EXPERIMENTAL

2.1. Mud Brick Samples

Two mud brick samples from Abu-Sir (Old Kingdom 1st Dynasty) and Mataria (Roman Period) were studied. The samples were very friable and had pale grey colour.

2.2. X-Ray Diffraction Analysis

The samples were ground in an agate mortar to a fine powder, pressed in the specimen holder, and then mounted in a Philips X-ray diffractometer. The operating conditions were : Generator : Cu K_α radiation (1.5418 A°) with Ni filter, 40 Kv, 20 mA current tube, speed : 0.1, chart : 5, Range : 1 x 10^3, time constant : 1, and silt : 0.1.

2.3. Chemical and Atomic Absorption Analyses

Complete chemical analysis of mud brick samples was carried out. Also the samples were immersed in deionized water for 24 hours, and the washing water was analysed for determination of the following ions and groups : Na, K, Ca, Mg, Cl, SO_4, CO_3.

2.4. Thin Section Analysis

Mud brick samples were sectioned, mounted on microscopic slides. Different minerals of each sample were identified using a Leitz polarizing microscope.

2.5. Consolidation

Three cubes 5 cm^3 were cut from each mud brick sample, then treated with tetraethoxysilane [TEOS], trimethylmethoxysilane (MTMOS), and methylmethacrylate-butylacrylate (MMABA) copolymer separately by penetration through capillary rise. The first two consolidants were used without dilution, but the last copolymer was diluted in 1:1 toluene and xylene. After one month the samples were treated once again, then allowed to stand for one month before examination with scanning electron microscope.

2.6. Scanning Electron Microscope (SEM) Examination

The treated samples were sputter-coated with gold (10 nm thickness) then were examined by SEM to compare the action of the consolidants and whether they filled pores, and the shape of the polymer links between grains after the polymerization process.

3. RESULTS

3.1. Abu-Sir Mud Brick

X-ray diffraction data of this sample Fig. 1 (a) indicated that it consists of α-quartz α SiO_2 (5-0490), Anorthoclase (Na, K) $AlSi_3O_8$ (9-478), albite Na $AlSi_3O_8$ (10-393), and trace amounts of biotite K(Fe, Mg)$_3$ $AlSi_3O_3O_{10}$ $(OH)_2$ (2-0045), kaolinite $Al_2Si_2O_5(OH)_4$ and montmorillonite $Na_{0.3}(Al, Mg)_2$ $Si_4O_{10}(OH)_2$. n H_2O (29-1498). Thin section examination Fig. 2 (a) showed quartz crystals (white), and large grains of orthoclase (simple twinning) in a matrix of fine grained silt and clay minerals, and organic materials. Most of the constituting grains were angular. Chemical analysis showed that it consists of 84.8% (by wt.) insoluble in HCl (silica and silicate minerals), 8.22% Al_2O_3, 1.30% Fe_2O_3, 0.67% Na_2O, 3.21% K_2O, 1.20% CaO, and 1.25% MgO. Atomic absorption analysis of the sample washing water showed that it contains 0.042 Na^+, 0.017 K^+, 0.015 Ca^{2+}, 0.003 Mg^{2+}, where volumetric chemical analysis confirmed the presence of 0.015 Cl^-, 0.004 SO_4^{2-} and 0.03 CO_3^{2-}.

SEM micrographs of this sample after treatment with TEOS, MTMOS, and MMABA are shown in Fig. 3 (a, b, c) respectively. In the case of TEOS the polymer network was formed on the grains and constitute links within pores. MTMOS forms less a continuous layer on the grains and also did not succeed in creating good links between grains. The copolymer shows a spongy form of the unhomogenous resin links.

3.2. Mataria Mud Brick

X-ray diffraction data of this adobe showed that it consists of the following minerals: α-quartz α-SiO_2 (5-0490), albite $NaAlSi_3O_8$ (10-393), anorthoclase (Na, K) $AlSi_3O_8$ (9-478), and trace amounts of biotite K(Fe, Mg)$_3$ $AlSi_3O_{10}(OH)_2$ (2-0045), and montmorillonite Na_n (Al, Mg)$_2$ $Si_4O_{10}(OH)_2$. n H_2O (12-219). Thin section analysis of the sample demonstrated quartz grains, some small and others large, plagioclase feldspar (Lamellar twinning) in a matrix of fine grained silt and clay minerals. Chemical and atomic absorption analyses of this sample showed that it contains 78.0% (by wt.) insoluble in HCl (Silica and silicate minerals), 9.58% Al_2O_3, 3.50% Fe_2O_3, 0.68% Na_2O, 5.04% K_2O, 1.40% CaO, and 2.48% MgO. Its washing water contains 0.038 Na^+, 0.017 K^+, 0.008 Ca^+, 0.002 Mg^{2+}, 0.012 Cl^-, 0.003 SO_4^{2-}, and 0.03 CO_3^{2-}.

SEM micrographs of the sample after treatment with TEOS, MTMOS, and MMABA are given in Fig. 3 (d, e, f) respectively. It is clear that TEOS was precipitated as nodules and penetrated through pores and around grains. MTMOS Fig. 3 e showed that links were formed also between grains but there are still large areas where little precipitation of the polymer occured. MMABA did not succeed in forming network links of the polymer.

4. DISCUSSION

The properties of mud brick and its durability to weathering depend to a great extent on their constituents and the interactions between them. Also, on the local environmental conditions. The amount of sand which is mostly the major component, silt or clay minerals which act as a binder, and the existence of organic matter, limestone, or fired brick, all play an important role in the deterioration process.

In the present work, results showed that ancient Egyptian mud brick samples consist essentially of quartz, plagioclase and potash feldspars in a loose packing matrix of silt and clay minerals, and organic materials. The author thinks that the main internal causes of deterioration of the examined mud brick were the loose packing and the angular ill-sorted constituting grains of different sizes. The cement material was not distributed regularly between quartz grains. There are large areas of fine silt and clay particles, where other areas have concentration of loose angular quartz grains as could be seen from thin section analysis and SEM micrographs (Figs. 2, 3). Also, the percentage of silt and clay is much more than in the ideal adobe stated by

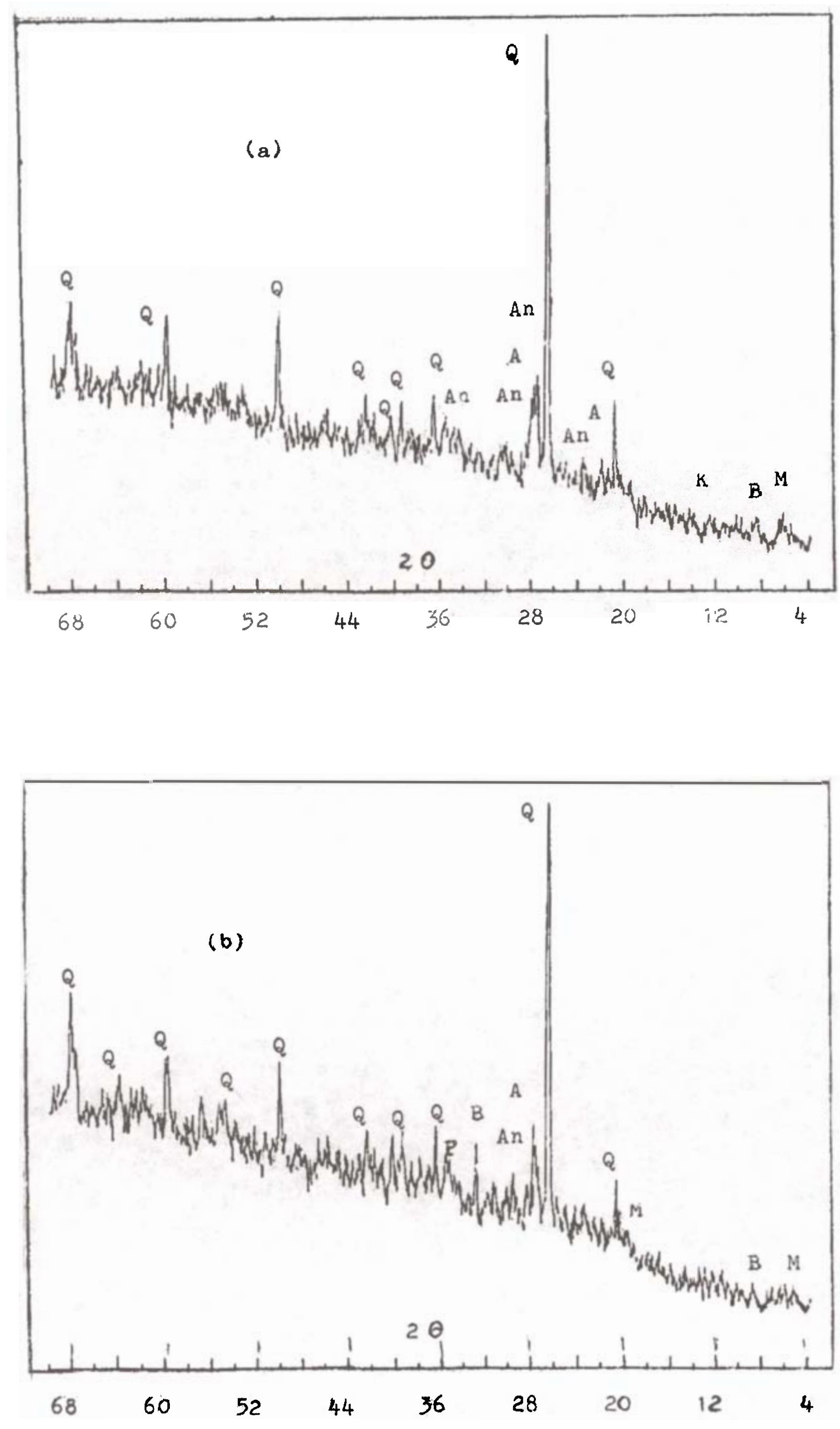

Fig. 1. X-Ray diffraction patterns of Abu-Sir (a), and Mataria (b) mud brick. Quartz (Q), Albite (A), Anorthoclase (An), biotite (B), Kaolinite (K), and Montmorillonite (M).

Clifton [3, 4]. The adobe based on different clay minerals may react to increasing water content. Montmorillonite adobe will be much more responsible to compressive deformation than a kaolinite one for the same amount of absorbed water [5].

Water is a serious factor for adobe deterioration. Absorption of water causes swelling of clay minerals and evaporation give rise to shrinkage, cracking, and breaking. The location of Abu-Sir excavation is near cultivated land; the adobe structure walls were found immersed in water due to the high water table level in this area. So, effect of water on adobe is erosion of surface along cracks and fissures, leaching of clay and silt matrix, and dissolution of soluble salt [6, 7]. Migration of soluble salt occurred towards the surface by evaporation, and recrystallization took place at the surface led to adobe deterioration.

Temperature fluctuation between day and night in both excavation sites is another possible factor for physical weathering of adobe in Egypt. Swelling by humidity in the early morning, and shrinkage at mid-day cycles likewise, may be implicated. Also, thermal stress and unequal expansion of the different constituents takes place giving rise to adobe disintegration.

Wind borne sand and detritus materials mechanically attacked adobe in both areas causing its abrasion. Riederer [8], has noted the intense mechanical attack of wind on stone in tropical countries.

The application of consolidants is very important for adobe conservation, which transform in situ into a polymer confer adobe new properties of durability and weather resistance. In the present work it is found from the obtained data that TEOS is the most suitable consolidant for the studied Egyptian adobe. It has low viscosity and penetrates well through adobe structure. Hydrolysis takes place by moisture in air and in adobe itself forms a network Si-O polymer in its structure and ethanol is evaporated. This agrees with the acceptance of Fielden [9], Gamarra [10], and Lewin [11] that TEOS with or without MTMOS and MEOS respectively as a surface treatment for adobe. The author's current research is the application of MTMOS as water repellent material after treatment of adobe with TEOS . MMABA is excluded because it may cause cracking by time and effect of U.V. radiation in situ, this in addition to the weak formed links in adobe structure.

5. CONCLUSIONS

Deterioration of mud brick in Egypt at Abu-Sir and Mataria excavations is due to the usual causes (ground water, thermal cycling, wind abrasion) but is accelerated by the adobe texture. Ill-sorted and loose packing of the different size constituent grains. TEOS was found to be the best consolidant for Egyptian adobe structure.

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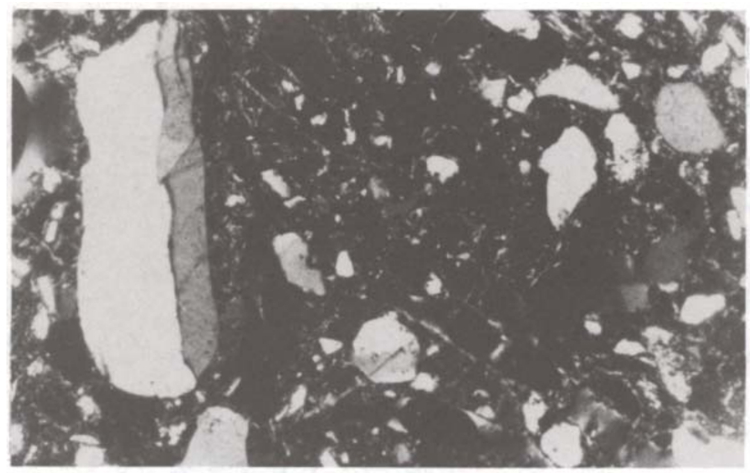
a



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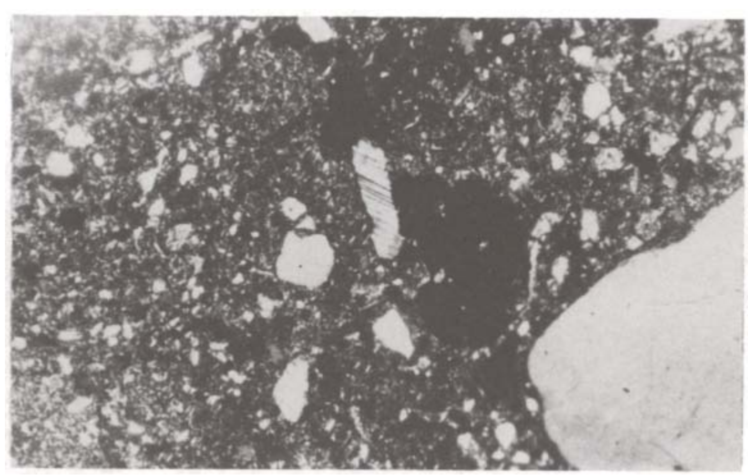

Fig. 2. Thin section photographs of Abu-Sir (a), and Mataria (b) mud-brick showed quartz, potash and plagioclase feldspars in a matrix of silt and clay minerals. x nicols, 6.3 x.

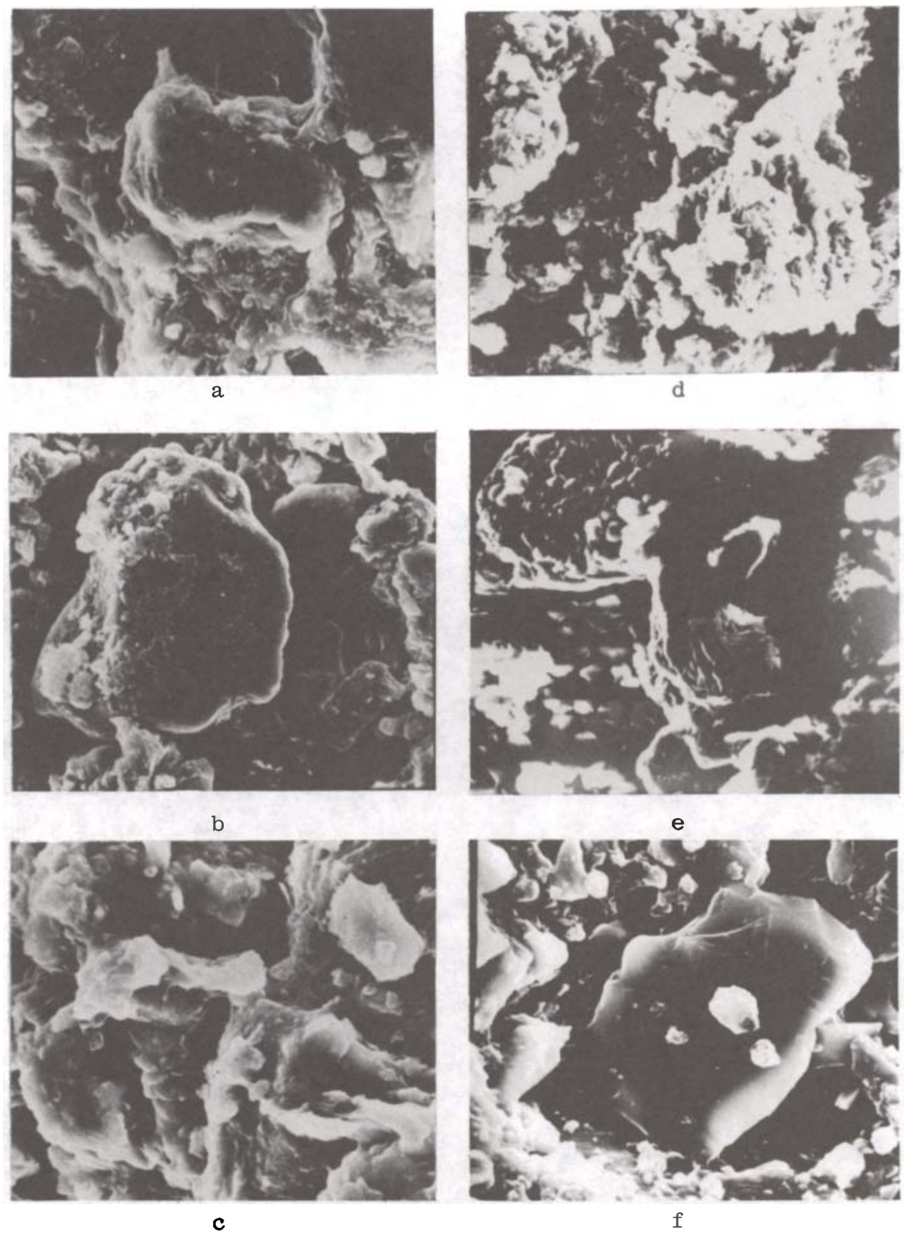

Fig. 3. SEM micrographs of Abu-Sir mud brick (a, b, c) and Mataria mud brick (d, e, f), after treatment with TEOS, MTMOS, and MMABA respectively, 400 X.

ABSTRACT

THE KEZIER GROTTOES, in the Xinjiang Autonomous Region of China, were carved in mudstones and sandstones. These natural sediments are poorly consolidated and behave like earth, disintegrating rapidly when immersed in water. Extensive research tests are reported on the use of potassium silicate of high molar ratio $SiO_2 : K_2O$ (typically 3.8) together with magnesium fluorosilicate and, in some instances, silanes such as methyltriethoxysilane as consolidants for the sediments. These yielded water-resistant products. Freeze-thaw, salt-resistance, accelerated aging, and water-absorption tests are reported. In field tests, walls were wrapped in gauze, wetted with glycerine and covered with plastic to prevent rapid drying and the formation of K_2CO_3.

KEYWORDS

Cave art, China, Consolidation of sediments, Grottoes, Magnesium fluorosilicate, Potassium silicate

THE WEATHERING CHARACTERISTICS OF THE ROCKS OF THE KEZIER GROTTOES AND RESEARCH INTO THEIR CONSERVATION

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Introduction

The Kezier Grottoes (Fig.1) are located in the Xinjiang Autonomous Region of northwestern China. They were carved in Tertiary mudstones and sandstones which are so poorly consolidated and cemented that they disintegrate immediately upon being wetted. In this respect they are similar to man-made earthen materials.

Fig.1 Kezier Grottoes; view near Cave 18 on the western side.

In 1986 the grottoes were surveyed, and it was noted that rapid deterioration was occurring despite the extremely sparse rainfall in the region. What little precipitation occurs is focussed into run-off channels that dissect surfaces and periodically cause collapse of large sections. Within the grottoes alkaline salts also cause flaking of the wall paintings.

In order to understand the characteristics of disintegration and develop strategies for consolidation and protection of the grottoes, a research program was undertaken. This addressed the mineralogy, chemical composition, soluble salts, and extensive laboratory and in-situ tests of consolidants. Accelerated aging tests are presently underway.

Rock Characteristics and Their Physical and Mechanical Properties

Lithological characteristics:

The geological strata of the grottoes region is the upper unit of the Tertiary period. The sediments are lacustrine in origin and are comprised of mudstone, sandstone, as well as lesser amounts of coarse sandstone, and gravel mudstone. The sandstone is grey to greyish-green, and its mineral components are mainly quartz, feldspar, as well as a lesser amount of a black mineral. Typically the thickness of single bed was 3-4 m. The cementing agents are calcareous or calcareous-mud, and the binding properties are poor, as shown by rapid disintegration of the rock in rainwater.

The rock walls in the grottoes have five to six layers of mudstone, the thickness of each being about 2 m. They are brown or grayish brown in color and contain soluble salts with locally fine gypsum layers, which weather easily.

Microscopy:

This work was carried out by the Geological Institute of the Academy of Sciences of China. Comprehensive chemical analysis, X-ray diffraction analysis, differential thermal analysis and scanning electron microscope examination has been done. The sandstone was poorly cemented and contained a great deal of carbonate (36.5% or so), and other soluble salts such as NaCl, $MgCl_2$, and $CaSO_4 \cdot 2H_2O$. After being fully submerged in water the rock lost its strength and completely disaggregated (Figs. 2, 3). The mudstone contained 5 -6 % montmorillonite.

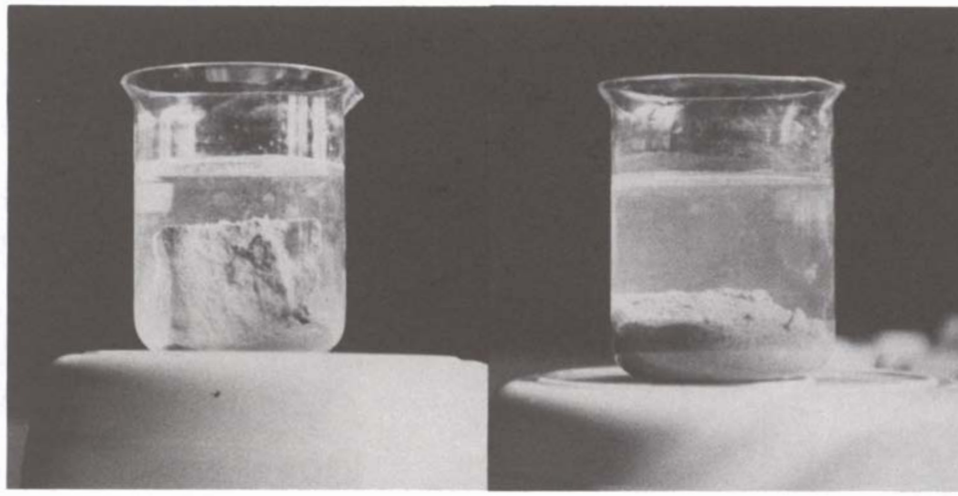


Fig.2 Photograph showing sample of the rock immediately after being placed in water.

Fig.3 Photograph showing the same sample (fig.2) 10 minutes later.

Table I Physical properties:

Sandstone:

bulk specific gravity	= 1.86g/cm³
specific gravity	= 2.72
porosity	= 20.9%
pore volume	= 0.113 cm³/g
mean pore radius	= 27.7 x 10^{-5} cm
water content	= 1.55 - 7.3%

Mudstone:

bulk specific gravity	= 2.01 g/cm³
specific gravity	= 2.74
void ratio	= 0.267
water content	= 2.74%

Table II Mechanical properties:

Semi-weathered rock:
S_t = 0.86 kg/cm²
S_c = 18.23 kg/cm²

Weathered sandstone:
S_t = 0.66 kg/cm²
S_c = 13.93 kg/cm²

Semi-weathered mudstone:
S_t = 23.58 kg/cm²
S_c = 497.8 kg/cm²

where S_t = tensil strength,
and S_c = compressive strength

Physical properties and Mechanical strength:

The physical properties are presented in table I. In view of the fact that the sediments were so poorly compacted and fragile, a point loading instrument was used for tests of mechanical strength. The advantage of this method is that it avoids the problem of irregular samples, while allowing for the examination of seriously weathered sample surfaces. Typical averaged values of mechanical properties are presented in table II.

Consolidant Testing

Selection of materials:

Chemical consolidation should improve the physical and chemical properties of the rock and their water-resistance, thereby stopping their deterioration due to rain. The protective measures we considered using were treating the rock with weather-resisting chemicals.

According to the properties of the rocks and climate of the Kezier Grottoes, we decided first that the prerequisites for the selection of consolidants were improved water-resistance and compressive strength. In view of the fact that the rock is poorly compacted, the consolidants should have good penetration, show resistance to freezing and weathering. Because the chemical materials were not used directly on the mural paintings within the grottoes, a little difference in color was tolerable.

From the first, we intended to use potassium silicate for treating the rocks and invited our colleagues of the Administrative Unit of Binglingshi Grottoes, Gansu Province to join in the tests. Two preliminary in-situ test series, and many laboratory tests, were carried out in October 1986 and May 1987. Strength increased because of the use of potassium silicate, but initially depth of penetration and water-resistance were not sufficient. Thus potassium silicate was not used for large-scale treatment at that time. In order to further the project, our institute then researched and developed several new chemical weather-resisting materials based on particular grades of potassium silicate together with other additives.

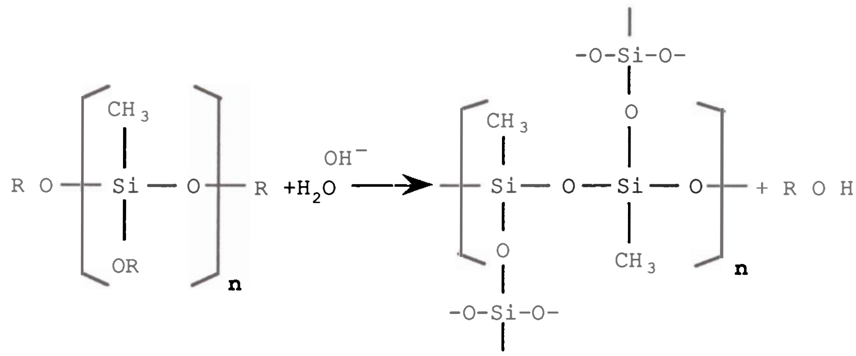
Test principles:

The rock of the Kezier Grottoes consists of quartz, feldspar and carbonates; it is fragile, flakes on rubbing, and disintegrates at once in water. Because the main component of the rock is silicon dioxide, a chemical consolidant which can form an inert silicon dioxide or similar compound was selected. Potassium silicate is weather-resistant but is strongly alkaline (pH 14), thus acidic magnesium fluorosilicate was added to neutralize the alkali and generate inert silicon dioxide and other compounds that would consolidate the rock and leave an inert substrate:

$$2K_2O \cdot nSiO_2 + MgSiF_6 \cdot 6H_2O + 2H_2O = 4KF \cdot 2H_2O + MgF_2 + 2(n+1)SiO_2,$$

where n is the molar ratio of $SiO_2 : K_2O$.

In addition, organic silicon compounds such as methyltrimethoxysiloxane or methyltriethoxysiloxane can form high-molecular silicone under the action of a weak basic catalytic agent:



where R is ethyl (C_2H_5) or methyl (CH_3)

This reaction is fast. In order to meet practical usage, it is necessary to regulate the amount of water and hardening agent as well as increase the amount of alcoholic solvent to slow the reaction. The alcohol serves also to slow the increase in viscosity as the polymerization proceeds and thus facilitates penetration into the rock.

Tests to determine the optimum formula:

A great deal of work on the selection of the best formulas suitable for consolidation of the Kezier Grottoes was necessary. Because of serious weathering of the rock, samples which could be used for tests were limited and it was impossible to obtain many samples for tests. Potassium silicate of molar ratio of $SiO_2 : K_2O$ over 3.4 has been used abroad; in our country potassium silicate of highest ratio 4.1 in liquid state can be produced. In brief, the formula developed was based on an aqueous solution of potassium silicate -- whose value was from 3.4 to 4.1 but mainly 3.8, diluted four-fold with water -- and was also reacted with magnesium flouorosilicate.

Adding magnesium fluorosilicate to potassium silicate solution precipitates catkin-like silicon dioxide immediately. The test called for brushing diluted potassium silicate solution onto the opposite two sides of the sample until it was permeated completely. After seven days of drying it was brushed with 3% magnesium fluorosilicate solution until completely permeated. After a further seven days of drying it was brushed with 5% magnesium fluorosilicate solution.

Samples for testing depth of penetration were brushed on one side only until permeated completely. The size of the sample was 5x5x5 cm. The main advantage of organic silicones such as methyltriethoxysilioxane was its superior water-resistance. However, the high cost of this material prevented its use in the Kezier Grottoes. In these experiments a group of tests of composite materials of inorganic materials and the organic silicones was involved.

In the course of the experiments it was found that if only simple brushing was done, without any wrapping of the samples, then poor penetration occurred on the second application, and the surface was suffused with white. The reason is that after brushing with potassium silicate solution the surfaces dried too quickly and crystals of potassium silicate aggregated on the surface. This converted into silicon dioxide and potassium carbonate after contact with the air. A thin impermeable layer often formed on the surface, preventing the second and third brushings from penetrating. However, if after brushing the samples were wrapped with gauze wetted with glycerine, the moisture evaporated slowly and the potassium silicate remained in the inner part of the samples, such that white potassium carbonate did not form on the surface. Subsequent brushing with 3% magnesium fluorosilicate solution, or 5% for third time, allowed easy penetration. After brushing with organic silanes the samples also were covered with gauze wetted with glycerine, which reduced the volatilization and prevented organic silicone resin from forming on the surface and creating a glossy, reflective layer.

Judging from indoor tests, potassium silicate of low molar ratio had a low strength and uneven penetration while the samples consolidated with potassium silicate of ratio 3.8 had a high strength and even penetration of about 5 cm. For samples treated with potassium silicate of ratio above 3.8 the strength did not increase.

Tests in-situ:

We selected seven rock walls of Kezier Grottoes (Fig.4), each with area of about 1 m^2. After physical tests in-situ to determine the rebound strength, samples were sent to Beijing for testing depth of penetration and water-resistance. Analysis of test results showed that the pure inorganic materials gave deep penetration and high strength, but water-resistance was poor. On the other hand, organic silicones gave good water-resistance, but the strength was poor and the penetration was uneven. We concluded that using composite inorganic and organic materials for consolidating the rocks of Kezier would, ideally, provide the best protection.

Fig.4 Site testing.

Systematic Tests:

In order to verify the test data further, we selected two of the better formulas and divided the test samples into two groups. Group A was the composite material and Group B the inorganic material.

Formula A:
potassium silicate of molar ratio 3.8
3% magnesium fluorosilicate
5% magnesium fluorosilicate
methyltriethoxysiloxane 100
ethanol 70
hardening agent SCP 0.8

Formula B:
potassium silicate of molar ratio 3.8
3% magnesium fluorosilicate
5% magnesium fluorosilicate

Examination of Consolidation Materials

Preparation of samples:

In order to make the data from laboratory tests and those from the in-situ tests comparable, we made it a rule that the preparation of the samples in the laboratory must be identical with the consolidation treatment in-situ. Thus, in the process of consolidation of the samples only spraying or brushing was used; submerging of the samples was not allowed, and that guaranteed the reliability of test data.

Density and porosity:

Mercury injection porosimetry was used to measure density and porosity. It was found that the density of Group A was somewhat higher than that of Group B: Both A and B were sprayed, and both A and B had much higher density than the original rocks.

The calculation of the porosity was by conversion between density and pore volume. The results showed that the porosity of group A samples was much lower than that of group B and original rocks.

Pore volume and mean pore radius:

The pore volume and the mean pore radius were measured for group A and group B. The pore volume of group A was 0.01664 cm^3/g, and was lower than that of 85% of the original rocks whose value was 0.11267 cm^3/g. At the same time it obviously was lower than that of group B. The mean pore radius of group A was higher than that of the original rocks but lower than that of group B.

Strength:

Two methods to measure strength in the laboratory and in-situ were used. In the laboratory, samples (5x5x5 cm) were sprayed on opposite sides. After drying, the sprayed sides were vertically measured by the method of point loading. The tensile strength of S_t = 2.26 kg/cm^2 and compressive strength of S_c = 47.51 kg/cm^2 were 3.4 times greater than those of the weathered rocks and 2.6 times greater than those of semi-weathered rocks. They were also higher than those of group B.

With regard to measurement in-situ, because the concentration of consolidant decreased with depth into the sample, the use of the point loading method for measurement was impossible, and we used the rebound method to measure the surface strength of rock. The surface strength of the original rock was too low to calculate its real strength; thus only the change in rebound value before and after treatment is used to describe their change of strength.

All the rebound values of the original rocks were less than 10, and indentations occurred on the rock surfaces after the measurement. The mean rebound value of Group A was about 15, while that of Group B was about 13. Only a trace of indentation occurred on the treated rock surfaces after the rebound measurement.

Tests for depth of penetration:

Measurement of penetration was based on the disintegration of the original rocks after submersion in water. In laboratory testing only one side of the sample of the 5 cm cube was sprayed which, after drying, was fully submerged in water. The unconsolidated part of the sample disintegrated, and this method showed that the depth of penetration of consolidation was more than 5 cm. Tests for penetration depth in-situ with the same basic method proved that the depth was 4-5 cm.

Tests for water-resistance:

Test samples for water-resistance were divided in two. One was submerged for a long time. The samples, 5 cm cube were sprayed on all sides and fully permeated and cured, then submerged in water. From 6th August 1987 to the present, none have disintegrated, whereas the original rocks disintegrated in less than 10 minutes. The other test was to dry and wet the samples alternately by submersion in water for 24 hours and then by placing them in an oven at 60°C for 72 hours to dry. Some 16 cycles have been completed so far without disintegration .

Water absorption tests:

These determined the amount of water moving through the sample surface per unit area with time. The purpose was to compare the change of capillarity and the water-resistance of surfaces of the rock before and after spraying. The samples were sprayed on one side then prepared into rectangular columns of 2x3x5 cm, dried and weighed and then the sprayed surface of 2x3 cm was brought into contact with water. Later it was weighed and the amount of water moving through the sample surface per unit area was calculated. A plot of water uptake with time was constructed. Both laboratory & in-situ results were determined. For group A the water-absorbing capacity was 0.008 g/cm^2 in 2 hours in-situ, and 0.34 g/cm^2 indoors, and the capillary rise of water was 2 cm in 2 hours. The water-absorbing capacity of the original rocks could reach 1.15 g/cm^2, and capillary height could reach 5 cm. in 10 minutes. For group B the water-absorbing capacity was 0.89 g/cm^2 in 90 minutes, and capillary height of 5 cm in 35 minutes. It was thus clear that the water-resistance of group A has greatly increased.

Freeze-thaw tests:

The 5 cm cube samples were fully sprayed, oven-dried and weighed, then submerged in a vacuum chamber for 1 hour, and placed in a freezer at -20°C ± 2°C for 4 hours before being taken out and thawed at room temperature. This process completed a cycle. From the results of nine cycles, the freezing-resistance of group A was better than that of group B, as well as the original rock.

Tests for salt resistance:

The preparation of the samples was the same as for the freeze-thaw tests. Samples were placed in saturated sodium sulfate solution for 20 hours, then dried at 60°C for 72 hours. After five cycles the stability of the samples of group A was clearly better than that of group B.

Tests for aging:

The protective materials were sprayed on thin samples 4x50x100 cm, and then put into aging apparatus of WE-SUN type, the temperature was controlled at 40°C, and sprayed with water every 3 hours. The apparatus has run for 1000 hours so far. Cracks occurred on the samples because of their thinness, and part of the samples of group A weakened at the corners; most of the samples of group B loosened and disintegrated. Tests are continuing.

Morphological observation:

The rock samples before and after treating were observed with the scanning electron microscope. It turned out that the composite materials either had sealed the sample surfaces of group A, or had filled the pores, but the pores had not been sealed completely. Flake-like inorganic materials also occurred on the rock surface (Fig. 5) and to a depth of 3 cm; flake-like or catkin-like inorganic material also covered the rock surfaces of samples of group B, but pores were filled in to a lesser extent, and some mineral grains were not covered with inorganic consolidant. Under the polarizing microscope we observed the composite materials partly filled in the pores to a depth of 1 cm in group A. On the surfaces of the samples the composite materials covered the minerals thicker than 1 cm. Tests in situ 2 were observed under crossed polarized light, it could be seen that the pores on the rocks' surfaces increased, and many minerals could be resolved. The composite materials showed small granular structure, and the inorganic materials showed catkin-like silicon dioxide.

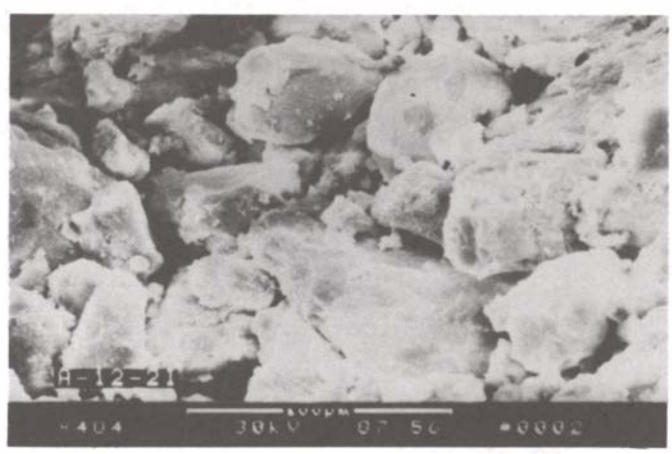


Fig.5 Scanning electron micrograph of the coating material covering the minerals in the rock sample.

Conclusion

Practicable methods of protecting the site against erosion by water were developed. These methods used spraying, or brushing of potassium silicate solutions of high molar ratio of SiO_2 : K_2O (typically 3.8), with other inorganic additives, on the surfaces of the rocks. In some tests these procedures were combined with alkylalkoxysilanes, but the high cost of these materials prevented extensive field use. The problems of K_2CO_3 efflorescence were largely eliminated through use of the appropriate ratio of silicate and by covering the surfaces with glycerine-impregnated gauze to retard drying.

ABSTRACT

Conservation of the eighth century B.C. mud brick architecture at Gordion, Turkey, has been long overdue. Partial burning helped preserve some of the mud brick, but little has been done to protect it since excavation over thirty years ago. Two methods of intervention have been tested: consolidation with acrylic resins and protection with a coating of mud plaster. Both methods are viewed as temporary treatments that can be replaced when a more permanent protective treatment is found.

KEYWORDS

Conservation, architecture, mud brick, consolidation, acrylid, mud plaster.

PRESERVING THE EIGHTH CENTURY B.C. MUD BRICK ARCHITECTURE AT GORDION, TURKEY: APPROACHES TO CONSERVATION

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Introduction

There are many individual factors that contribute to the decay of excavation sites, but by far the most destructive and frustrating is the combination of neglect and slow decomposition through time. It is inexcusable that the great relics of our past dissolve away unattended while new trenches are dug nearby. The primary concern at this time should not be the discovery of new civilizations, but the preservation of those already uncovered.

The ancient Phrygian city of Gordion serves as a perfect example of a site where such action is necessary. While this paper will concentrate only on the needs of the site's mud brick buildings, Megaron 1 and Megaron 4, it is by no means intended to obviate the attention needed by Gordion's other monuments.

A Brief Site History and Description

Megaron 1 and Megaron 4 belong to the Early Phrygian citadel that is the dominant feature of Gordion today. Excavations conducted by Rodney S. Young between 1950 and 1973 and by Mary Voigt in 1988-1989, under the auspices of the University of Pennsylvania, have uncovered numerous occupation levels within the 300 x 500 m "City Mound" situated on a flat plain along the Sakarya River about 100 km southwest of Ankara, Turkey (See fig. 1). Settlements run the gamut from Early Bronze Age strata in the tell's lowest layers to an early Roman Empire encampment in the topmost regions of the mound. The exposed sections of Early Phrygian Gordion lie in an enormous 150 x 200 m trench cleared from the eastern half of the City Mound during Young's excavations. Little was known of the Phrygians until Young's intensive search made it clear that by the end of the eighth century B.C. Phrygia, with Gordion serving as its capital, was a prominant civilization exerting considerable control over central Anatolia. It is also apparent that Gordion reached the height of its prosperity under the rule of the legendary King Midas and that Phrygia met its demise as a dominant power under his leadership when Gordion was burned and destroyed by the Kimmerians, a group of nomadic invaders, in ca. 700 B.C.

The Early Phrygian citadel, called the "Destruction Level" because of the significant fire damage and collapse of many of its structures, is divided into three main precincts: a palace area to the northwest, a high terrace to the southwest supporting two long service structures, and a multiroomed building that bordered the

Figure 1. Gordion, overall plan of destruction level.

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city's northwest fortification wall. To the southeast is a massive gate complex that served once as a monumental entrance to the city but was undergoing a rebuilding project at the time of the Kimmerian conflagration. The burned remains of the two mud brick megara stand in the palace area, which consists of two courtyards separated by a heavy enclosure wall running northeast-southwest and each containing groups of megara. Megaron 1 is located in the southwest corner of the "enclosed courtyard" nearest the gate complex (so called because of a light retaining wall that separates it from the gate structures), and Megaron 4 is situated on the northwest side of the "open square", the courtyard northwest of the heavy enclosure wall.

Megaron 1

Excavated in 1956 and dated to the ninth or eighth century B.C., Megaron 1 is one of the earliest buildings of the Destruction Level. The structure measures 9.5 x 17.5 m and consists of a porch and inner room, each with a central hearth (See fig. 2). Entry was gained through two central doorways placed symmetrically along the longitudinal axis, one leading from the enclosed courtyard to the front porch and the other piercing the cross wall between the porch and the inner room. Except for a stone socle the megaron's walls were built entirely of mud brick and wood and then covered with a thick coat of mud plaster. The existing walls are three bricks thick with alternating niches and piers on the inner and outer faces. The niches were left by wood posts set into the wall faces on the exterior and interior of the building and are wide enough to suggest pairs of posts. The remains of the wall faces stand to a uniform height of about 1 m, while the central row of bricks rises somewhat higher and is pierced at regular intervals by holes. A horizontal beam topped off the vertical posts and bricks of either wall face at this level. The voids through the inner brick core were for short crosspieces that tied the framework of each side together. The level above this first horizontal beam would have had its own posts and another wood leveling course above them.

During the fire, the roof--made of beams covered with a layer of reeds coated in turn by clay--collapsed along with all the walls above the first leveling course. The copious amounts of wood used in the timber framework and roof beams in conjunction with the highly flammable reeds must have made the blaze quite intense. This was made apparent by the vitrified state of in situ mud plaster that melted in the fire and began running down the walls. Many of the individual mud bricks, particularly those located in the niches left behind by burned out posts, were baked hard and blackened because of their proximity to the flaming timbers.

Megaron 4

Megaron 4 was completed at the end of the eighth century just before the Kimmerian fire. It rests about 2 m above the other buildings of the open square upon an extension of the citadel's

Figure 2. 1956- Megaron 1 just after excavation.

Figure 3. 1961- Megaron 4 just after excavation.

southwest terrace. The structure has exterior dimensions of 12.3 x 22 m (See fig. 3). The interior arrangement consists of a very shallow front porch and a deep inner room connected by a central doorway in the cross wall between the two rooms that is matched by a doorway of the same width between the facade's returns. Unlike Megaron 1, the walls were made of solid mud brick without a wood frame and range from 1.32-1.45 m in thickness. There are no vertical niches in the inner and outer faces and no bricks preserved at a uniform level to suggest horizontal string courses. Charred wood and reed found on the floors indicate that Megaron 4 had a roof similar to Megaron 1, and a pattern of post holes in the main room suggests that there was once a three-sided gallery level in the rear chamber along the back wall and flanks. As with other examples of this gallery system found in many buildings of the Destruction Level, Megaron 4's gallery provided its own support without piercing the actual wall fabric.

While Megaron 4 was razed almost to its foundations, it seems that the absence of a half-timbering system did not fuel as severe a fire as that encountered by Megaron 1. The roof and gallery no doubt burned and collapsed followed by the subsequent fall of most of the superstructure. However, the in situ sections of mud brick, which vary in height from 0.25 meters to 0.75 meters, do not exhibit the same degree of burning and discoloration as those in Megaron 1.

Decay of the Megarons

Climatic conditions in the Gordion region are inordinately harsh. The majority of the average annual 350 mm of precipitation falls during the winter months and is accompanied by freezing temperatures (-15°C). During the summer, when excavations are ongoing, the area is quite dry and windy with only limited rainfall, exceedingly high temperatures (40°C-45°C), and correspondingly low humidity (10%-20%). This is an ideal environment for the promotion of mechanical weathering on the excavation site, particularly for unprotected surfaces that are broken down by repeated frost-wedging and wet-dry cycles and washed or blown loose by rain and wind.

Of all the erosion at Gordion the most notable post-excavation deterioration has taken place on Megaron 1 and Megaron 4. Until the 1989 season, no intervention had been taken to circumvent the slumping of the earthen masonry that makes up the remaining walls of these monuments except for an application of acrylic resin to a small section of Megaron 1 in 1982 (see "Previous Treatment" below).

Megaron 1 seems to be better preserved than Megaron 4, although it was excavated five years earlier and has been exposed to the environment for a longer period of time. This is more than likely due to the more complete baking that the mud bricks of Megaron 1 underwent from the intense temperatures generated by the ignited timbers of the building's wood framework. Another factor

Figure 4. Overall deterioration of Megaron 1.

may be that Megaron 4 is in a more vulnerable position. It is elevated above the level of the other buildings in the palace area and does not benefit from any shade during the day or any sort of protection from wind and rain. Megaron 1, on the other hand, is bordered by terracing walls built at later stages of the citadel that extend along its southeast flank and rear wall. These offer at least some shade and certainly act as screens from some of the elements.

Despite the discrepancies in states of preservation both megarons are in terrible condition. For the first several years after it was unearthed, Megaron 1's individual bricks and their courses were clearly discernible and uninterrupted except for the niches left by timber posts. Now, after thirty-four years of continuous contact with snow, rain and wind, many sections of the walls have dissolved completely, while the outer surfaces of others have "melted" so that the walls' original forms are barely recognizable (See fig. 4). In megaron 4, the bulk of the walls have either disappeared or have been covered with slump that was once original brick surface. It is only at the returns of the cross wall and facade that one can still make out the seams that demarcate different bricks.

Previous Treatment

Prior to 1989, the only treatment undertaken on the mud brick architecture was the application in 1982 of an acrylic resin (Acryloid A-21) on a small section of Megaron 1 [1,2]. It is unclear whether the application has been effective in preventing further deterioration, particularly as the treatment was not carefully documented or photographed. Furthermore, it is doubtful that the high molecular weight (and corresponding viscosity) of the resin permitted deep penetration.

On-site Examination and Treatment Tests

In 1989, we made a detailed examination of the mud brick architecture of Megara 1 and 4 and discussed the deterioration of the mud brick, the previous treatment, the sampling of burned and unburned sections, proposals for treatment tests, and future research. We requested and received permission from the Turkish Archaeological Service to take samples of the mud brick. The analysis of samples will determine the condition and structural strength of the burned and unburned mud brick.

Megaron 1 was chosen as a site to test two treatment methods for the protection of the mud brick architecture. The first proposal was to cover a small mud brick section/pier with a modern mud plaster (or mud stucco) as a protective coating, which, although obscuring detail, was not unlike the protective mud plaster that had originally covered the surface. The second proposal was to consolidate another small section with an acrylic colloidal dispersion (Acrysol WS-24), both as a comparison to the mud plaster application and to the previous acrylic treatment (Acryloid A-21) applied in 1982.

Toward the end of the season we carried out both of these tests, after first photographing, cleaning, and sampling different sections of the mud brick. One of the local workmen, who had been replastering the mud brick in the Gordion excavation compound (house and walls), mixed up a thick mud plaster and carefully applied it directly over one of the mud brick sections/piers. This was allowed to dry and touch-up was done in any cracks that developed. Detailed photographs were taken to record the treatment so that any weathering and change over the winter can be compared in 1990 (see fig. 5).

Figure 5. Section/pier of Megaron 1 after mud plaster application.

Prior to the on-site consolidation test with Acrysol WS-24 we experimented on a large fragment of mud brick found lying in the middle of Megaron 1. This fragment was taken back to the excavation compound and consolidation tests were begun using different concentrations of WS-24 and using two different methods of application.

Acrysol WS-24 was chosen as the consolidant because of its excellent physical and chemical properties [3]. It is a very fine particle-size acrylic polymer of high molecular weight dispersed in a water medium, and its extremely low viscosity ensures deep penetration. The hardness and durability of the set resin (after water evaporation) should provide more than adequate strength and protection against adverse climatic conditions. After setting, the resin is removable with solvents (e.g., flushing with acetone), but in practical terms this would be very difficult.

The first method chosen was by simple wetting: dripping and pouring various concentrations of WS-24 directly onto the mud brick. This was done only to one end (the small end) and it was found that concentrations up to 20% resin were readily absorbed by the porous brick, except in the areas where the brick fabric had been sintered or fused by the destruction fire. A 4% solution of WS-24 was chosen for the complete consolidation, and after thorough wetting (at which point a build-up of consolidant occurred on the surface), the brick was left in the shade to dry.

In order to assess the penetration of the consolidant, the brick was broken in half after forty-eight hours when it felt dry to the touch. It was easy to see where the consolidant had penetrated because it had slightly darkened the substrate and, in fact, had not completely dried in the center. Complete penetration was achieved except on the one side where the brick was burned.

Figure 6. Consolidation test using 4% WS-24 on mud brick.

The second application test was carried out by placing the remaining brick fragment in a closed system and allowing a 4% solution of WS-24 to percolate or "wick" up from the bottom. The brick was placed in a double-lined plastic bag with enough solution at the bottom to cover one-quarter of the brick, and the plastic bag was then sealed. The percolation rise of the consolidant was monitored over the next several days, and once the solution had approached halfway up the brick (in thirty-six hours), more solution was added to replace that which had been absorbed (see fig. 6). After another forty-eight hours, the consolidant had reached about three-quarters of the way up the brick, but hardly moved after that. The brick was therefore removed the next day, and an unsuccessful attempt was made to break it (again to assess the penetration of the consolidant). The unconsolidated end was immersed in 4% WS-24, and when dry, the fragments were returned to the find spot on site to weather the winter. The brick was photographed and a careful examination will be done in 1990 to assess its condition and the effectiveness of the consolidation.

Figure 7. Section/pier of Megaron 1 after 4% WS-24 application.

On site, one of the smallest and most deteriorated sections/piers in the SW corner of Megaron 1 was consolidated using WS-24. In this case, a 4% solution was both sprayed on with an atomizer and dripped from the top into one of the most exposed areas. The section, although only four courses high and two wide, literally drank up the consolidant, and over 2 liters of solution were applied. As the upper bricks became saturated, an excess of resin began to build up in one area, and it was decided that the end point had been reached. The excess was lightly brushed off using deionized water. Photographs were taken throughout all stages of the treatment in order to record and compare any changes the next summer (see fig. 7).

Additional samples of mud brick were taken from Megaron 4. Analyses of the mud brick samples will be undertaken to determine their composition and cohesive strength, and, together with the analyses of the ancient mud plaster, will aid in selecting a future treatment.

Conclusions

The condition of the burned Gordion mud brick makes it an extremely interesting and problematic case study in the preservation of in situ earthen architecture. Two methods have recently been tested for the protection of the mud brick. The first treatment test involved the complete covering of a mud brick section with a mud plaster or stucco. The second method tested returned to the use of an acrylic consolidant, but in a finely dispersed aqueous medium. Both treatments have advantages and limitations, when one considers the nature of the intervention as "exterior" or "interior".

The mud plaster stucco approach is more in keeping with what the building had as an original facing, but now that the building is exposed to the elements, it will require regular maintenance. In addition, the effectiveness and protection has to be weighed against the somewhat disturbing aesthetic appearance. Even so, the covering preserves the general appearance, and the intervention is minimal as it does not introduce any new and unknown materials into the mud brick.

The introduction of the acrylic consolidant WS-24, though apparently penetrating deeply, presents many unknowns, regarding its cohesive strength, localized concentration, and interior penetration. As a temporary conservation measure, it allows the current condition of the structure to remain visible while protecting the mud brick from further decay.

Until a suitable and effective consolidant can be found to completely protect the exposed mud brick architecture at Gordion, the decision will have to be made as to what temporary measure is most acceptable. Further tests and research are needed to assess both the physical requirements of the mud brick and methods for complete impregnation. The exposed architecture at Gordion offers an important opportunity and site for future study and immediate attention.

NOTES

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MATERIALS

Acryloid B-72, Acrysol WS-24: Acrylic resins, manufactured by Röhm & Haas, Philadelphia, PA; supplied by Conservation Materials Ltd, Sparks, NV, U.S.A.

CONSOLIDATION OF A NEOLITHIC EARTHEN SITE WITH POTASSIUM SILICATE

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ABSTRACT

This paper presents the results of an experimental study of consolidation with potassium silicate of a neolothic earthen site at Dadiwan, Gansu Province, China. Details of the preparation of the potassium silicate solution, its properties, and the mechanism of its action with montmorillonite - containing clay are described. The physical and chemical properties of the potassium silicate-clay composite were determined by testing and instrumental analysis. Calcium flourosilicate and aluminium silicate were used with the potassium silicate solution. Of crucial importance is the molar ratio of SiO_2 to K_2O. The optimum ratio is 3.8 - 4.0. Higher concentrations of K_2O give poor results through eventual formation of K_2CO_3 by atmospheric carbonation.

KEYWORDS

Consolidation, Potassium silicate, Montmorillonite

Introduction

Weathering is the most serious cause of deterioration of earthen structures, and a solution to the problem is urgently required. By investigation and analyses of the ruins of a neolithic earthen site at Dadiwan, Qinan County, Gansu Province in northwestern China, it was concluded that montmorillonite contained in the clay is one of the main factors contributing to weathering. The purpose of the present research was to find ways to reinforce this type of earth by enhancing the degree of consolidation by chemical means and thus prevent weathering.

Ruins of house of Yangshao Period in Dadiwan, Qinan, Gansu [1]

At the beginning of the 1980s, two rare, large ruins of houses, designated F_{405} and F_{901}, built during the neolithic period of late Yangshao, were excavated at a site at Dadiwan. A unique aspect of the site is that the floors (in area about 300 and 131m^2 respectively) are made of burnt Liaojiang stone (the depositional calcium carbonte in loess), which is quite similar to contemporary man-made concrete type ceramics. These floor materials are believed to be the earliest known cement and man-made concrete filler.

Fig. 1 - The F_{901} ruins of the house of the Yangshao period in Dadiwan.

Selection of Consolidants

The clay in the structures at Dadiwan contain some montmorillonite. As is well known, montmorillonite can absorb much water into its layered structure and swell considerably. Upon drying the clay contracts. Such an alternation of expansion and contraction accelerates weathering damage. It was the intent of the research to reinforce the earthen structures by permeating them with inorganic cementing materials which are similar to and can react with the clay, thereby improving the cementation and make the earth more weatherproof and stable. This, in theory, is an ideal way to reinforce and prevent earthen ruins from weathering.

Initially, tests on the material from Dadiwan were conducted with polyvinylalcohol, polyvinyl-acetate emulsions, and sodium and potassium silicate solutions of different molar ratios of metal oxide to silicon dioxide. Less than ideal results were obtained. Subsequently it was found that using potassium silicate with a high molar ratio of $SiO_2 : K_2O$, together with appropriate solidifying agent, cross-linker and surface active agent to reinforce the structure by permeation is an ideal method for consolidating.

At first, it is necessary to determine the optimum molar ratio of $SiO_2 : K_2O$ for the aqueous solution of potassium silicate. In the case of too low a ratio, after the potassium silicate and clay have reacted with each other, too much K_2O will remain which will form K_2CO_3 under the action of the atmospheric CO_2 and moisture:

$$K_2O + CO_2 \rightarrow K_2CO_3$$

If the potassium carbonate that results is not treated in time, or is removed, the stability of the cemented mass will be impaired. When the ratio is too high, it has a weakened cementation, which causes the strength of the solidified layer to decrease and, at the same time, tends to form a coagulated layer preventing the mass from being permeated to any depth. In such cases, spraying is difficult to carry out and does not produce good results. How to determine the optimum modulus for the potassium silicate? Through cementing an amount of clay (C) containing some montmorillonite [2] with an aqueous solution of potassium silicate (PS) at the same concentration, but with different molar ratios of SiO_2 to K_2O, a PS-C composite mass is made. Then test properties such as CO_2 - resistance, weatherability, water resistance and thermostability may be determined. By these tests the optimum ratio of the potassium silicate solution was determined to be 3.8 - 4.0.

Solidifying agents and cross-linkers are also important factors affecting the stability and applicability of the PS-C material. Tests have been carried out on more than 10 types of solidifying agents such as aluminium trichloride, iron trichloride, sodium fluorosilicate, calcium fluorosilicate and potassium aluminium sulphate. Judged by the solidifying speed and the stability

of the PS-C-cemented mass, calcium fluorosilicate as the solidifying agent was found to be best. Through testing, powdery aluminium silicate was selected as the cross-linker.

Preparation of Potassium Silicate of Correct Molar Ratio

An industrial potassium silicate (molar ratio about 2.6) was diluted with water to a specific gravity of 1.3 and then caused to react in a 15 L stainless steel autoclave. It was heated by jacket-water bath to 100°C and stirred vigorously. At the same time, powdered silicon dioxide (80 mesh), mixed with warm water into a paste, was added gradually into the autoclave. The operating pressure rose to 21 kg/cm^3. About two hours later, samples for determining the ratio were taken from the autoclave. If the required ratio was obtained, the PS preparation was considered complete. The PS obtained with an optimum ratio is a somewhat yellowish, thick colloid. It would be substantially colorless if purer starting material was used. The measured surface tension, density, viscosity and pH are given in Table 1.

Table 1. Surface tension, density, viscosity and PH values of potassium silicate (P.S.) solutions at given temperatures

P. S. solution	Temperature (oC)	Surface Tension (dyne / cm)	Density (g/cm^3)	Viscosity (CP)	PH
Original	8.0 +/- 0.1	76.67	1.2529	118.89	
	25.0 +/- 0.1	75.17	1.2488	18.729	
	15				12
Diluted*	8.0 +/- 0.1	74.31	1.0478	1.7789	
	25.0 +/- 0.1	72.81	1.0449	1.1425	
	15				10 - 11

* - Potassium silicate solution diluted with water by 4X, + 1% $CaSiF_6$

The PS diluted four times with water is colorless and transparent. The procedure for preparation of the working solution is as follows:

Determine the dilution according to the requirements for application and measure the water required. Weight out respectively the $CaSiF_6$ and $Al_2(SiO_3)_3$ required and add them to the water. Stir the mixture and then pour it into the PS solution. Finally, add about 10ppm of NNO as diffusion agent and stir uniformly. It is then ready for spraying.

Preliminary Analysis of Mechanism of Action Between the Clay (C) and Aqueous Solution of High Molar Ratio of Potassium Silicate (PS).

X-ray Diffraction Analysis

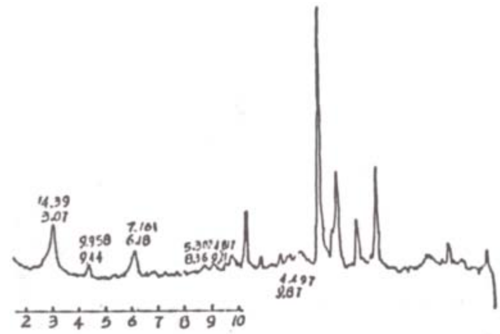

Fig.2 X-ray diffraction spectrum of clay containing montmorillonite.

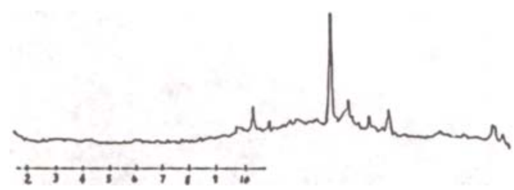

Fig.3 X-ray diffraction spectrum of PS-C.

Fig.2 is the spectrum of the clay containing montmorillonite; Fig.3 is the spectrum of PS-C. The spectra show that the clay minerals' crystallinity was destroyed by treatment with the PS. The clay minerals have turned substantially into an amorphous gel. Even if montmorillonite still exists in the clay, the clay treated with the PS solution, which is mainly potassium silicate, will have a reduced space between layers, i.e., the C-axial length will be reduced, thus resulting in reduced expansion by absorbed water due to exchangeability of the montmorillonite with the potassium ions.

Infrared Spectral Analysis

Fig.4 is the infrared spectrum of clay containing montmorillonite; Fig.5 is the infrared spectrum of PS-C. The infrared spectrum shows that the OH peak intensity near 3500 cm -1 of the mass has dropped considerably, and the OH shifted by 10 wave numbers. This is another reason why the PS-C cemented mass has higher water resistance.

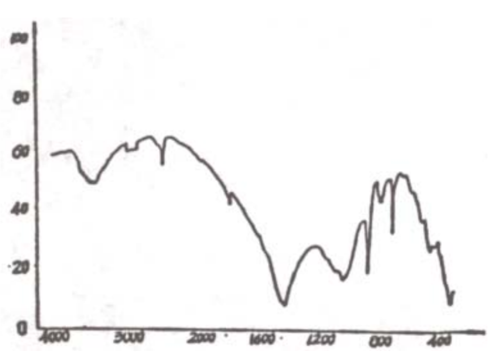

Fig.4 Infrared spectrum of clay contained montmorillonite.

Differential Thermal Analyis (DTA)

Fig.6 is the differential thermal curve of the clay containing montmorillonite; Fig.7 is the differential thermal curve of the PS-C. The differential thermal curves show that the clay has the first endothermic peak at 84°C, the second at 561°C and the third at 754°C, while the three endothermic sygnals of the PS-C are of 113°C, 684°C and 837°C respectively. That is to say, after the clay was treated with PS, its water-loss temperature rises. It is possible that part of the clay-absorbed water is converted into structural water on the clay resulting in an increase of the strength and water resistance.

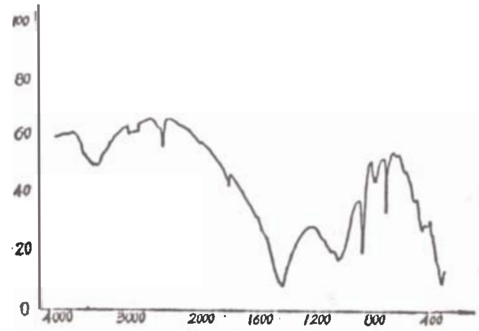

Fig.5 Infrared spectrum of PS-C.

Fig.6 Differential thermal curve of contained montmorillonite.

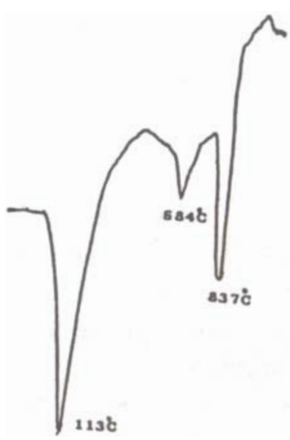

Fig.7 Differential thermal curve of PS-C.

Scanning Electron Microscope (SEM) Examination

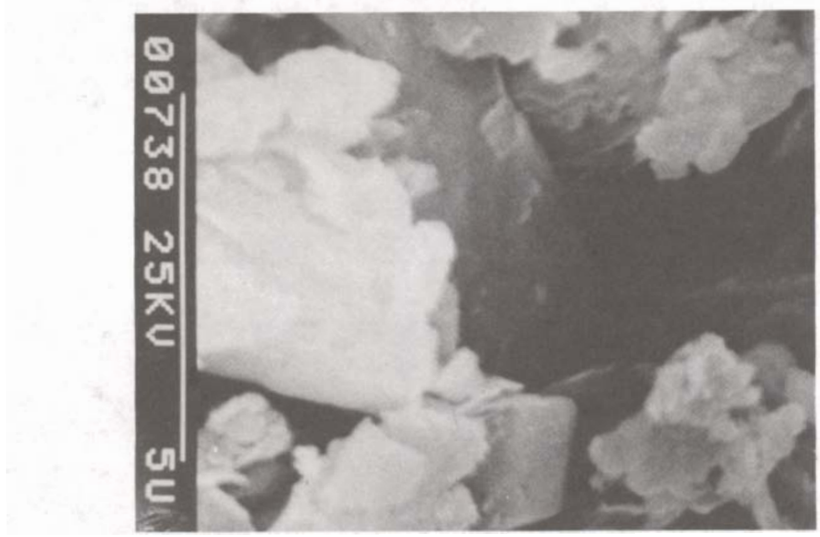

Fig.8. SEM photograph of clay containing montmorillnite, 9000 x.

Fig.8 is a SEM photograph of clay contained montmorillonite; Fig.9 is a SEM photograph of PS-C. The SEM photograph shows that an interwoven fibrous network of crystals, similar in structure to that found in hydrated gypsum, has formed. This is an important factor in imparting to the PS-C composite good water resistance and mechanical strength.

Fig 9 SEM photograph of PS-C, 9000 x.

Testing Main Physical and Chemical Properties of PS-C

Water Resistance

Test pieces of PS-C of different molar ratio were immersed in water until they disintegrated. Among test pieces which have been immersed for 16 months, the PS-C of high ratio (3.8-4.0) have not disintegrated, while those of lower ratio (below 3.5) disintegrated in a much shorter time.

CO_2 - Resistance

Resistance to CO_2 is one of the important indexes in examining the stability of the PS-C cemented mass. In the case of too low a ratio the potassium silicate will retain too much K_2O. This K_2O will gradually create K_2CO_3 under the action of CO_2 in air and cause the PS-C cemented mass to effloresce in moist air. This can be established by the following test: Small pieces of PS-C of different molar ratio are placed in a vacuum desiccator with water at the bottom and filled with CO_2. It is found that PS-C test pieces made with potassium silicate of low ratio went white and viscous on their surface within a few days. Samples of high ratio showed no change after months.

Weatherability

Small test pieces were placed outside and exposed to sunlight for six months, then tests were carried out for water and CO_2 resistance. It was found that test pieces of high molar ratio were stable and did not disintegrate when subsequently placed in water. Also no deterioration took place under CO_2 saturated with water vapour.

Basicity of the PS-C Cemented Mass

Because the PS solution is a strong-base, it might be considered that clay treated with the PS solution (that is the PS-C cemented mass) will be unstable and effloresce in air. This is not so: the silicon and aluminium in the expansible clay can cement with water and calcium only in a highly basic environment and increase the mechanical strength and stability of the PS-C cemented mass to a great extent. High basicity has become a simple and effective way to improve the engineering performance of expansible clay and has been widely used in civil engineering at home and abroad.

The original PS solution we used had a pH = 12 which dropped to about pH = 10 after being diluted. The PS-C cemented mass is quite stable which has been proven by the tests outlined above and in site applications.

CONSOLIDATION WITH PS OF THE F_{901} REMNANTS OF THE LATE YANGSHAO PERIOD HOUSE AT DADIWAN.

In August 1984 and in October 1985, site consolidation was undertaken on the weathered remains of the Yangshao house by spraying with PS solution. A 13-meter wall, one cooking stove and two post holes have been consolidated. Up to now, five years later, no abnormal changes have taken place on the surface of the structures. In our view an ideal effect was achieved (Figs. 10, 11).

In the site testing the weathered remnants of the house were sprayed once, twice and three times respectively for the purpose of comparison. From observations made over more than one year it is recommended to spray three times. Structures which have been sprayed three times still have good permeability, that is to say, it is possible to do fourth or fifth treatments if necessary.

CONCLUSION

Testing for consolidating the weathered archaeological earthen structures at Dadiwan, and on-site application, have shown that the PS solution reported here can achieve an ideal result in terms of strengthening the substrate while retaining good permeability. As seen by physical and chemical properties, testing, X-ray diffraction, infrared, scanning electron microscopy and differential thermal analyses, the PS-C is a kind of stable weatherproof inorganic composite which does not undergo marked changes in appearance. The tests have achieved the aim of changing the cemented state of clay containing montmorillonite through reinforcing by means of permeation with PS. There is, however, a problem to be solved through future research, that is, when applied to wet earth the PS shows poor permeability and a low rate of solidification. Furthermore, SiO_2

coagulates on the surface under such conditions and this results in a reduction in the consolidation and strengthening effect.

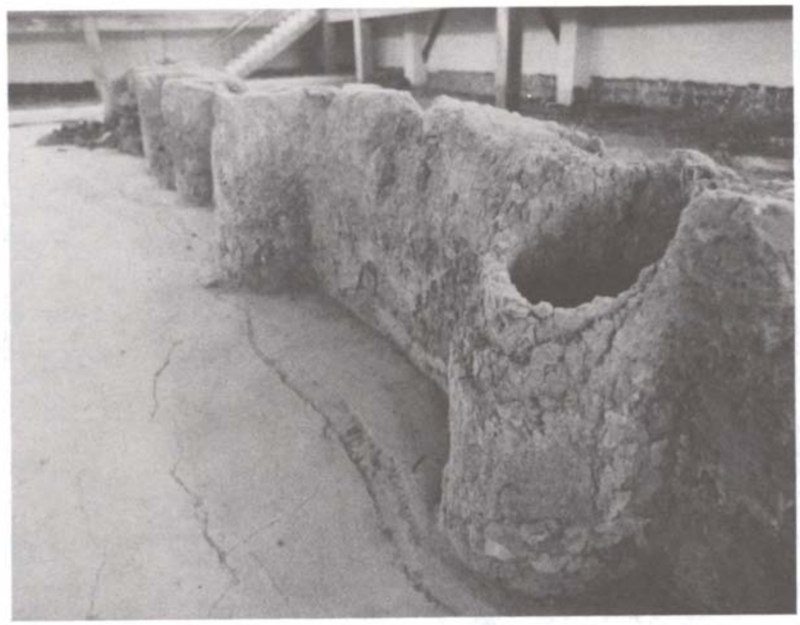

Fig. 10. The wall and skeleton pillar on adherent wall of F_{901} house-ruins after consolidation. (Photo, March 1990.)

Fig.11. The Pillar hole of propping beam wooden pillar of F_{901} house-ruins after consolidation. (Photo, March 1990.)

Acknowledgements:

We thank Mr. Wang Hengtong and Mr. Wang Qi for their assistance in the experiments.

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4 Nishiura, T., and Li, Z., *'Experimental Study on the Consolidation of Fragile Porous Stone with Potassium Silicate for the Conservation of Cave Temple in China'*, Conservation of Far Eastern Art, IIC 12th Internation Congress, September 1988, Kyoto, 108-112.

[1] The late Yangshao period of Dadiwan is 4,900-5,500 years before present.

[2] Clay (C) containing montmorillonite for testing was taken from the North Cave Temple, Qinyang, Gansu Province.

GENERAL CONSIDERATIONS ON THE PRESERVATION OF EARTHEN ARCHITECTURE IN MINAS GERAIS, BRAZIL; A PROPOSAL FOR REINFORCEMENT OF A BRAYED MUD WALL STRUCTURE

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ABSTRACT

There is a considerable historical and artistic patrimony of earthen architecture in Brazil dating from the colonial period. A systematic study of the consolidation of this architecture is essential. This paper considers intervention methods for earthen structures as well as an analysis of their contents.

To illustrate the type of projects that have been undertaken in Brazil, a case study of the conservation of the Basilica of Our Lady of Pillar is discussed. This project involved the restoration of a severely deteriorated edifice, which required special analysis and structural reinforcement of the masonry of a brayed mud wall which had incurred static damage. The goal of the project was to maintain the old material while giving the masonry a new sustaining capacity, taking into account the original constructive system.

KEYWORDS

Conservation, restoration, brayed mud wall, pau-a-pique, adobe, moledo, reinforcement, consolidation.

Fig. 1: Wall with "moledo" base and adobe masonry. Tiradentes, Minas Gerais. Photo: Lima.

Brief Historical Overview of the Use of Earth in Architecture

The use of earth as a construction material dates to prehistoric times, to ancient Mesopotamia and Egypt. In Pre-Columbian America, its usage was widespread among the Aztecs and other North American peoples.

In South American countries such as Brazil, the Spanish and Portuguese introduced European techniques of earthen architecture during the early stages of colonization. As a result, the early urban architecture of these countries is characterized by features such as wide window sills, the predominance of walls over empty spaces, and specific wall thicknesses. Every type of architecture in the "mineira" (1) history of the eighteenth and nineteenth centuries--civil, official, or religious--was influenced. Earth became the most viable building material for structures and dividing walls of edifices because of the abundance of the material in the region and its environs and the mastery of the technique by artisans.

The construction systems that use this technique offer a variety of applications as seen in the edifices of our historical centers. Examples of earthen techniqeus are adobe and formigão (normally used for structural purposes, at least on the outside walls) and the pau-a-pique, taipa-de-sebe or taipa-de-mão for dividing walls and internal sealing.

Less frequently we find another material called moledo, equally characteristic of that region, made of decomposed clay, pebbles, and rocks. Because of its resistance (load-bearing capacity), it is also used in the structural masonry and dividing walls, in some cases exposed to open air. (See fig. 1.)

As an alternative to the use of earth, we find stone used as a material especially in edifices of monumental proportions. The use of stone inevitably increased the construction cost because of the difficulty of handling and transportation.
In a few cases rock is used for the entire structural system of the building, though in the majority of cases it forms only part of the structure, the foundations and corners, for example. Another advantage of stone is its decorative use.

General Considerations about the Preservation of Earthen Architecture

A. Systems conservation

Over the last six years, the National Artistic and Historical Patrimony Secretary (SPHAN) has exercised greater influence over the historical centers of the region Campos das Vertentes with the objective of repairing the damage occuring as a result of the social and economic decline in Minas Gerais. Some old edifices were in critical condition. Others required intervention at specific damaged points, which were easily repaired. In other cases the stability of the building was compromised, requiring more extensive intervention. In the case of structures whose inhabitants kept up comprehensive maintenance--from the roof to water and electrical installation and sewage system--the physical condition remained sound, reducing conservation costs.

B. Urgent work staff

In order for SPHAN to be effective in the historical centers, the Federal Government established an "urgent work staff" to restore

1. The style representative of Minas Gerais (a state in Brazil).

Description of the Constructive Systems

Brayed mud wall: This system is one in which the walls are of massive monolithic mud, which is formed in wood moulds held in position by traverses and wood sticks.

Adobe: This material consists of mud bricks with dimensions of 20 x 20 x 40 cm. It contains vegetable fibers or manure. It is put to dry in shadow and, after a few days, in the sun. It differs from conventional bricks in that adobe is not baked in an oven.

Formigão: This variation of the mud wall is made by not sifting the mud but rather mixing it with stony earth to make a conglomerate-like concrete.

Pau-a-pique: This is a kind of sealing which consists of pieces of wood set perpendicular between the "baldrames" (the lower support) and the "frechais" (the upper support), attached by holes or nails. Normally, other thinner pieces, sticks, are attached on both sides. After the texture is made the mud is thrown and pressed on by hand.

Moledo: This is a conglomerate made of clays, "saibro" (fine gravel) and decomposed rock, removed in blocks from the mines, in the shape of cobble stones of varying dimensions. Because this material is very resistant, it is applied "in natura."

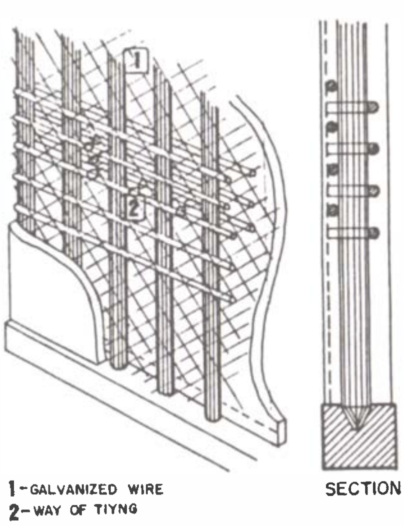

Fig. 2: Pau-a-pique wall. Illustration by Lima.

and maintain the architectural patrimony as well as furnishings. This staff is not sufficient to undertake all of the needed interventions and can only address the "most urgent" cases.

Through this staff the Brazilian Government is able to offer to the people of the historical centers, who are generally in need of financial resources, assistance in preserving their buildings. We offer, free of charge, the manual labor of specialized staff; private patrimony owners contribute the necessary materials when resources are available; SPHAN supplies the technical orientation.

C. Criteria and intervention methods

The first step in the restoration and conservation of a given damaged edifice is to examine the existing damage and to prepare a condition report. After verification of the financial condition of the resident, the subsidy is determined which the SPHAN will provide for the execution of the work.

If a decision is made to undertake the intervention, it is necessary to study the possible treatment approaches according to at least three criteria:

- The persistence in the use of the techniques, traditional or contemporary, which have been tested and which satisfy the purposes of the conservation project.

- The use of native material which is appropriate to the material being treated and which reduces costs.

- The historic authenticity of the object as well as its contemporaneity. Interventions should be indicated in distinct and transparent ways.

We can now delineate a chart of practical examples of solutions adopted for the treatment of certain materials.

D. Conservation of the wall

1. Pau-a-pique

We find the pau-a-pique system in several edifices, which show external deterioration due to contact with moisture caused by poor roofing or by soil saturation. In these cases, the solution is to eliminate the humidity or the surcharge and to investigate the rupture, disintegration, deformations, etc. that have occurred. From this point on we promote the repair of the masonry or, as an alternative, in situations of extreme disaggregation where repair is not possible, the option is reconstruction, using comtemporary techniques such as conventional fired brick, either solid or "emptied" ones or "sical" block (cellular concrete), etc.

1.1. Repair of the elements

-Paus-a-piques: those that present a useful section are maintained and conserved and rectified when necessary.

-Sticks: when completely deteriorated, new sticks are substituted.

-Mud wall: if losses are registered after the disaggregation of the plaster, the mud is often repaired using a mixture of mud-cement (~1:20), compatible with the old system in level of coefficient of dilatation. Eventually a layer of rough cast and two layers of final cast are applied.

In the most serious cases, when a considerable loss of mud is aggravated by the instability of the wood texture, a texture of galvanized wire is used on both sides to consolidate the whole system. (See fig. 2.)

2. Brayed mud wall

Monolithic (big block) masonry structure of large dimensions presents problems when it is directly exposed to open air. After the rough cast is dislocated, humidity (especially rain) disaggregates the structure. Also, structural problems arise due to fissures in the lower areas of the foundation, deterioration of the beams, etc. Usually, in the case of one- or two-story structures, the effects of the problem cease with the treatment of the problem--that is, if the roof is repaired or the foundation is reinforced, only the work of recomposing the damaged spaces remains. At most, it is possible to introduce an "atirantamento" (steel and wood wires to hold the walls together) on the masonry. In cases of excessive horizontal stress, this intervention consolidates the masonry with rigid structure.

3. Adobe and moledo (2)

Because of the peculiarities of these materials, they "behave" very well statically (rigidly), except in situations such as those that occurred with the brayed mud wall. Presently, there is no other method of intervention in these systems of construction.

The dimensions of these materials are considerable: adobe almost invariably measures 20 x 20 x 40 cm; moledo is quite variable, but its size is at least equal to the adobe brick. Usually they are used double in masonry, resulting in a minimum width of 40 cm, with the right enclosures.

4. General technical solutions

In any particular edifice there are different systems of earthen construction--structural masonry, both external and internal, and internal dividing walls. In certain situations there is a lack of cohesion in the junction of two systems which causes fissures on the corners. A galvanized iron texture can help to connect the masonry.

Every time we undertake an intervention on the roof of an edifice with structural systems of earthen construction, it is advisable to take advantage of the moment to execute a crowning belt, to connect the system by stabilizing the skeleton of the building. The effects of weather must be avoided, since the areas closest to the eaves suffer the greatest from accumulated rain water.

In order to alleviate the effects of ascending and lateral pressure of water on the masonry, it is advisable in certain cases to construct a ventilation ditch, a system whose purpose is to eliminate the direct contact between the masonry and the soil, by forming an intermediate "mattress of air."

A proposal for reinforcing a structure of a brayed mud wall. Specific case study: Basilica Cathedral of Our Lady of Pillar

A. The brayed mud wall

The brayed mud wall was largely used as a system of construction in the "Paulista Plateau" and in the state of Goiás. In the northeast, the use of this technique was not often utilized, but there is record of the use of this system of construction in 1660 in the city of Salvador, Bahia.
In Minas Gerais, the use of the mud wall was less frequently used. Other materials (wood, stone, etc.) were plentiful, and furthermore the region is quite uneven, a fact which favors the use of other techniques.

Reports of travelers from the nineteenth century (e.g., Richard Burton, 1868) have been found which prove the existence of civil and religious buildings constructed in "taipa" in several regions of the State; such is the case of the Basilica of Our Lady of Pillar in São João del Rei.

B. Basilica Cathedral of Our Lady of Pillar

This is an edifice made of brayed mud wall, dating from the early eighteenth century. The high altar contains the main chapel and altar piece, which was completed three decades later.

The construction includes an area of 1.056 m^2 with an average of 5.50 m height. The church square covers an area of 129 m^2, reached by a flight of stairs made of "cantaria" (carved stone). The construction consists of two parts, a posterior one which includes the high chapel and sacristry and another, anterior, which includes the main nave and the lateral corridors extending into the main façade, which was rebuilt during the middle of the nineteenth century in stone masonry. (See fig. 3.)

The main façade has a central door in the lower part, flanked by four smaller doors symmetrically set in relation to the central axis under five windows of the balcony finished by a triangular "frontão" topped by a stone cross. The façade is flanked by two towers provided with pyramid domes. All the details of the façade are made of carved stone. Inside, the temple is one of

Fig. 3: Façade of the Basilica Cathedral of Our Lady of Pillar. Photo by Lima.

2. Material made of decomposed clay, pebbles, and rock.

the most expressive of the "mineiro" baroque for its profusion of gold carving, mainly in the high chapel where proportion and harmony and grace predominate. The nave has seven lateral altars in the same style as the high chapel.

C. Reinforcement proposal

The building is settled in the southeast part of the town of São João del Rei, in the foothills of Rosario. (See fig. 4.)

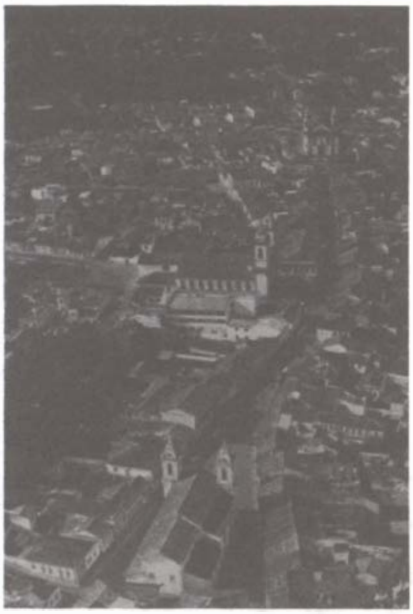

Fig. 4: Aerial view of part of the historical center of São João del Rei. In the center is the Basilica Cathedral. Photo by Lima.

In the time since the building's construction, the streets of the town have been paved, including those streets that begin behind the church and rise directly up the hill. This paving keeps the surface water from filtering down into the soil, as it did in former times. The resulting accumulation of water on the posterior part of the church causes erosion of the soil that holds the foundations at the right side of the building.

In addition, there is also the poor condition of the drainage system meant to collect rain water and conduct it to the sewage system.

These facts caused the "lisionamento" and the deformation of the right wall.

The deformation of the wall also caused the rupture of the eaves and dislocation of the tiles, allowing the infiltration of rain water on the mud walls over the course of many years. This caused the disaggregation of the earthen masonry, reducing its endurance, increasing the intrinsic tension of the material on the critical points of the structure, for instance in the "vazados" (empty spaces) of the doors, windows, niches, etc.

The altars at the right wall of the central nave, located at the openings that pass through the masonry, were in a severly damaged state. One could clearly see the lateral "flambagem" (as a result of pressure) of the carved wood columns that form the lateral altars.

As a first step, we removed the artistic elements, and we provided for the support of the "vão" (empty space).

The conservation of the roof had already been completed in 1986. An investigation into the stability of the building was elaborated, beginning with the investigation and geological study of the soil, in order to evaluate the support conditions, inspection and charting of the damage, with the setting of "testemunhos" (an instrument used to register the deformation) on the walls. These observations help to show the extent of the movement of the structure.

At the same time, we planned and implemented drainage on the posterior part of the building in order to conduct the surface water to the sewage system. Repair of the system for draining rain water from the roof was also proposed and implemented. (See fig. 5.)

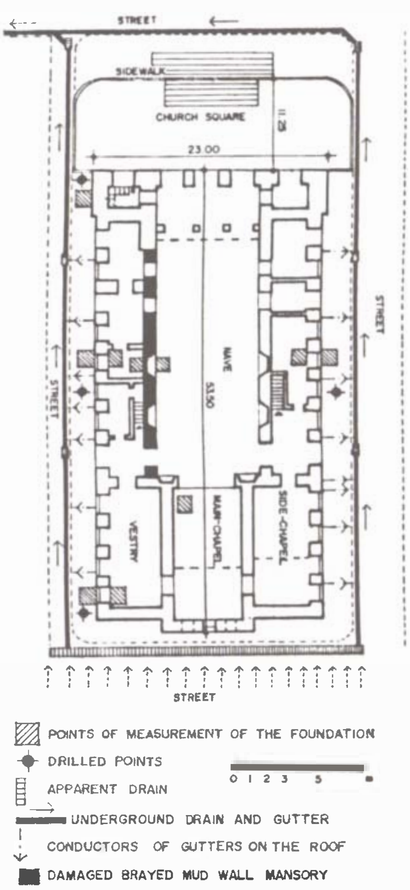

Fig. 5: Ground floor plan of Our Lady of Pillar. Illustration by Lima.

After this work was completed, we began to observe the damage by periodic inspection, to verify the condition of the deformations.

These steps were necessary to reduce the financial costs of the intervention, by first eliminating the causes of damage and then intervening to repair the consequences.

At present, we are elaborating the structural reinforcement of the mud wall and intend to prevent the reinforcement of the damaged masonry and in this way avoid its substitution.

We know all the patterns of reinforcement are based on the behaviour of the supporting structure. In the case of the mud walls, the supporting structures have the following characteristics: They are considered cyclopean structures, for the height-section relation of their pieces is low and so is its capacity to absorb horizontal stresses. The spring coefficient and the ductility both have low values. Another element to be considered is the low capacity of deformation in plastic regime, which means a material has only a limited capacity to dissipate energy without articulating. As mud is a very fragile material, after being damaged it is difficult to analyze the static behaviour; each new element presents differentiated dimensions and conditions of support, producing secondary efforts on the critical points.

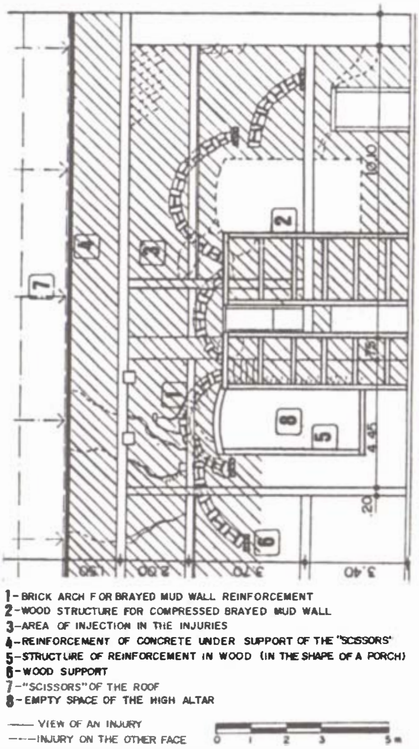

Fig. 6: Brayed mud wall reinforcement proposal. Illustration by Lima.

Thus, we consider that any proposal for reinforcement should take into consideration the original state of tensions, considering the elements working together. Also the fineness of the pieces should be considered. This is a basic fact for the qualification of the "portante" (load-bearing) capacity.

Some points of the proposed reinforcement are to be considered: The continuity of forms and volumes, the symmetrical distribution of the elements, improving resistance to tensions, the density and uniformity of the materials, the rigidness and ductility of the sections, the capacity of resistance compatible with the efforts and the limited capacity of deformation.

We then proposed reinforcing and consoliding the wall by filling the empty spaces and areas of loss with a mixture of soil-betonite-lime and reinforcing the empty spaces in order to support the surchages without modifying the original structural system of the walls.

The reinforcement involves installation of a parabolic arch of discharge over the empty space, in both sides of the wall and additional arches disposed upon the former in order to redistribute the strength lines near its original proceeding.

These arches will be made of baked mud bricks with mortar with a mixture of soil-cement.

The necessity of reinforcing the straps of the open space and improving the conditions of support of the "impostas" of the arch will be evaluated on site.

A moulding of the empty space will be executed in wood with a rectangular closed porch.

For the vertical sections that were crushed, a belt will be used with wood pieces on both sides, properly linked by transverse pieces. (See fig. 6.)

Conclusion

As one can observe from the text above, the task of preserving the earthen architecture in Brazil is still at a very rudimentary stage, without systematic studies showing the technical and financial difficulties found in this area where the Government is not totally aware of the need for a larger investment in research and labor. In recent times technical-scientific studies have begun to appear that support restoration work; this is developing slowly. Despite these problems, the work developed up to now has been rewarding. Quite satisfactory results can be obtained by using simple techniques, making it possible to save the majority of Brazilian patrimony from ruin.

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Seismic Mitigation

ABSTRACT

Quincha (or reed binding) is a type of construction used in Peru in colonial times and up to the first decades of this century. It is made of clay, reeds, and timber, materials with which high quality housing can be achieved and which have demonstrated good resistance to earthquakes. The present research, which comprises experimental and analytical studies, was directed at expanding basic knowledge on its structural behavior. The conclusions of this study have allowed for the proposal of simple rules of design. These rules can be used for the conservation of historical monuments.

KEYWORDS

Quincha (reed binding), structure materials, experiments, design, seismic behavior.

COMPORTAMIENTO ESTRUCTURAL DE LA QUINCHA

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Introducción

La quincha es un sistema constructivo empleado durante la colonia y hasta las primeras décadas de este siglo en el Perú. Los materiales usados en la quincha son tierra, madera y caña, con los cuales se logran estructuras livianas. En zonas urbanas, la quincha se usó mayoritariamente como segundo piso, sobre un primer piso de adobe. Este tipo de edificación brinda innumerables ventajas como hábitat en la costa del Perú, por el agradable ambiente que proporciona, por la seguridad que ofrece durante terremotos, y por su bajo costo. Luego del sismo de 1746, la construcción de quincha se adoptó masivamente por el buen comportamiento observado. La Universidad Católica del Perú y la Technical University of Nova Scotia, Canadá, con apoyo del International Development Research Centre of Canada, iniciaron en 1988 una investigación interdisciplinaria con el objetivo de promover el uso de edificaciones de quincha en zonas marginales de Lima. La investigación abarcó desde estudios experimentales hasta el diseño y construcción de diferentes obras. Este trabajo presenta mayormente los aspectos básicos de ingeniería estructural que sean de interés para un público amplio interesado en la construcción y conservación de edificaciones de quincha.

Características de la Quincha

Se describe a continuación el tipo de quincha usado en el proyecto de investigación de la Universidad Católica, haciendo alusión a otros tipos de quincha tradicional.

La cimentación, usada en diferentes obras construidas como parte del proyecto, consiste en una losa de concreto armada con caña (Fig. 1). En las construcciones tradicionales de quincha se encuentran cimentaciones de mampostería de ladrillo o de piedra asentada con cal.

Las paredes son formadas por paneles prefabricados de madera de dimensiones 0.80 m de ancho y alturas de 2 a 2.40 m, los que se clavan entre sí. Los paneles consisten en un marco de madera con travesaños como muestra la Figura 1. Una vez unidos los paneles se coloca la *estera,* tejido de cañas chancadas, que luego se tarrajea con barro. Los paneles tienen secciones de madera de 2.5 x 7.5 cm. El espesor terminado de los muros es 15 cm. Se usan paneles de dos tipos: paneles convencionales y paneles sísmicos (Figura 2).

El tipo de caña que se usa para las esteras y techo es el *carrizo* (Arundo Donax), el cual crece en los bordes de los ríos. Es muy común el uso de bambú partido y chancado (Guadua Augustifolia) y carrizo entero arqueado sobre travesaños de madera.

El techo es de vigas de madera, y cobertura de caña con mortero de cemento. Se usan vigas de madera de tornillo espaciadas a 0.8m. Las cañas proporcionan un aislamiento adecuado, a pesar de su reducido espesor. El mortero de cemento se aplica en espesores del orden de 2 cm, con lo cual se logra una cobertura liviana, durable y resistente a la lluvia. La quincha tradicional hace uso de la "torta de barro", una capa de barro de 5 a 10 cm de espesor. La Figura 3 muestra una perspectiva de la estructura.

Materiales

Como se ha mencionado, los materiales principales de la quincha son la tierra, madera y caña. Para la presente investigación se usó la madera denominada "Tornillo" (Cedrelinga Catenaeformis), proveniente del Oriente del Perú.

Se estudiaron diferentes especies de caña y bambú (1), obteniéndose los valores de la resistencia a la tracción. Por ejemplo para la caña brava (Ginerium Sagittatum) se observó una resistencia del orden de 2800 Kg/cm^2, semejante a la de algunos aceros.

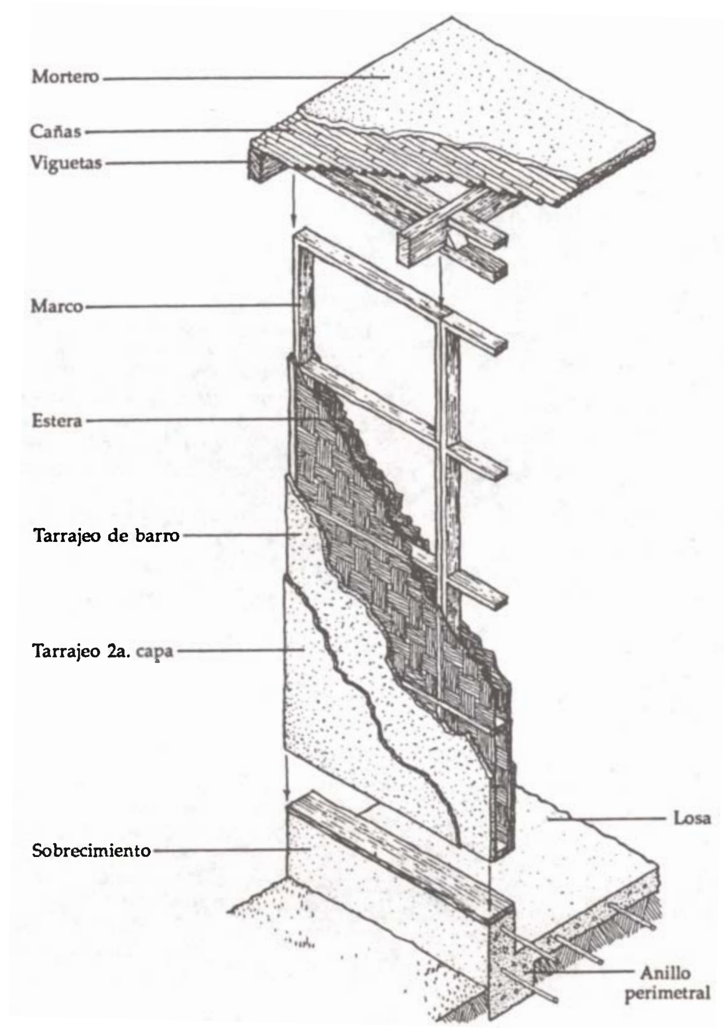

Figura 1 Detalle de Panel y Cimiento

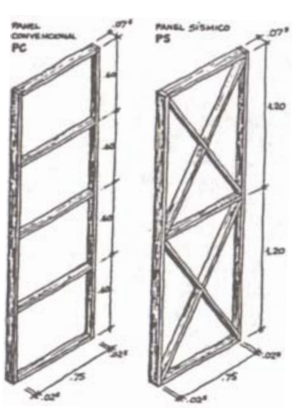

Figura 2 Tipos de Paneles

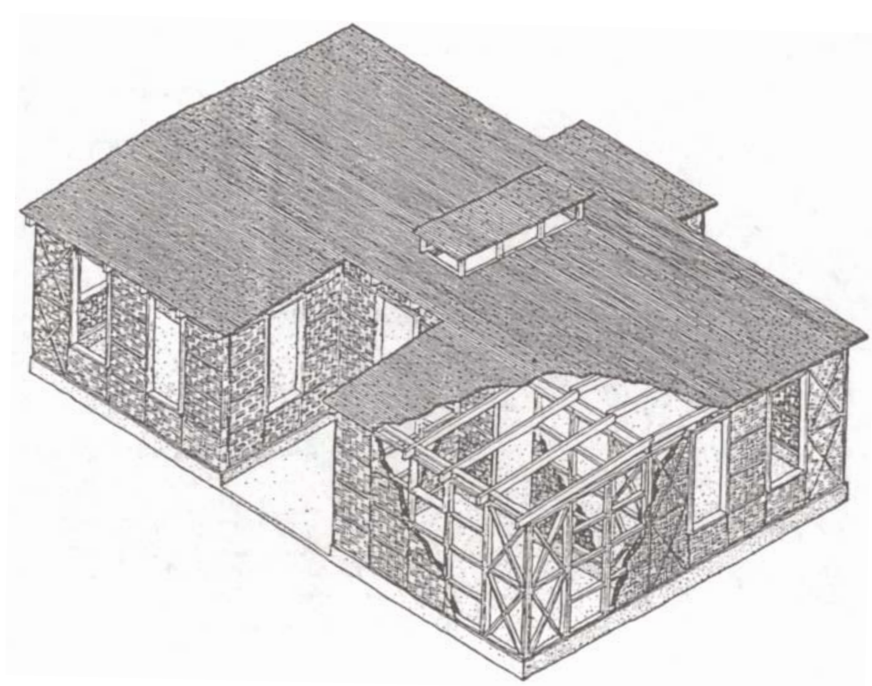

Figura 3 Estructura de Quincha

La "paja" puede ser cualquier fibra vegetal resistente y duradera, por ejemplo el ichu (Stipa Ichu que)crece en la sierra del Perú. También es posible usar césped, paja de arroz, etc. Es conveniente que la paja tenga fibras de aproximadamente 10 cm de largo.

La tierra es usada para el tarrajeo de las paredes en combinación con arena gruesa y paja. El tarrajeo se aplica en dos capas, cuyo espesor debe ser en lo posible 1.5 y 3/4 de cm. La capa delgada, la cual puede hacerse con arena gruesa o arena fina, permite cubrir las fisuras e irregularidades de la primera y darle un acabado final. Normalmente, la mezcla óptima (arena:tierra) está entre 1:1 y 1:2 por volumen para suelos de mediana plasticidad que son los más corrientes. Se añade una cantidad de paja equivalente al 1% del peso total seco. Cuando se observa excesiva fisuración, es necesario realizar pruebas para lograr una mezcla adecuada. El porcentaje que se añada dependerá de cuan arcillosa sea la tierra. La forma más práctica de determinar el porcentaje de arena gruesa adecuado es fabricar una serie de mezclas con proporciones en volumen, arena:tierra, de 1:3, 1:2.5, 1:2, 1:1.5, 1:1, con 1% del peso seco en paja, tarrajeandose paneles de prueba. Debe observarse la trabajabilidad de la mezcla y la fisuración al secar, escogiéndose la mezcla con adecuada trabajabilidad y que permita controlar la fisuración (entendida como solo la aparición de fisuras finas), con la menor cantidad de arena gruesa posible. El exceso de arena gruesa hace que la mezcla sea muy débil y fácilmente erosionable. Las Referencias 2-6, contienen diferentes estudios sobre las estructuras de tierra. La Referencia 4 trata el tema de la durabilidad de tarrajeos de barro.

Para el techo se usó (1) un recubrimiento de mortero cemento:arena gruesa en proporciones por volumen 1:6 y de 2.0 cm de espesor.

Ensayos de Laboratorio

Se realizaron diferentes ensayos para estudiar el comportamiento de las estructuras de quincha (1). A continuación se presenta un resumen en el que no se incluyen detalles y resultados técnicos.

La composición de los tarrajeos de los especímenes fue mantenida en proporciones aproximadas arena:tierra de 1:2. En algunos casos debido a la variabilidad de la plasticidad de la tierra, no fue posible mantener la misma proporción. La paja usada fue el ichu, en una cantidad igual al 1% del peso seco del material. La cantidad de agua fue definida de acuerdo a una trabajabilidad estándar medida con la aguja de Vicat (3). Las paredes de quincha fueron similares a las descritas anteriormente, excepto que el espesor fue de 5 cm en lugar de 7.5 cm.

Se realizaron diferentes ensayos de paneles para estudiar las propiedades mecánicas básicas, tales como su capacidad para resistir cargas verticales, las que son producidas por ejemplo por el peso del techo. Las resistencias obtenidas fueron bastante superiores a las que se dan en construcciones de 1 y 2 pisos, por lo cual esta solicitación no se considera crítica. Diferentes acciones, por ejemplo el viento, solicitan a los muros en dirección perpendicular a su plano. Con la finalidad de estudiar la respuesta de las paredes de quincha ante este tipo de cargas se realizaron experimentos observándose que el espécimen era capaz de sufrir deformaciones bastante altas, sin darse daños importantes y sin perder resistencia. Adicionalmente, se realizaron también ensayos dinámicos con la misma finalidad; verificándose nuevamente un buen comportamiento frente a cargas perpendiculares al plano de las paredes.

Ensayos de Paredes bajo Cargas Laterales

Este ensayo simula la acción de los sismos sobre las paredes mediante la aplicación lenta de cargas laterales. Se ensayaron 3 paredes de la forma mostrada en la Figura 4, a las cuales se les aplicó además de la carga lateral, una carga vertical de 2000 N por metro de ancho para simular el peso del techo. El objetivo del ensayo fue estudiar el comportamiento ante cargas laterales, y en particular determinar la influencia de la relación ancho/altura de las paredes. Los mecanismos de falla observados se indican en la Tabla 1. En todos los mecanismos de falla se pudo apreciar como parte del fenómeno la separación del tarrajeo y la estera. Como se aprecia, la resistencia por metro de ancho varía en menos de un 20% para los tres especímenes, por lo cual puede considerarse para fines prácticos que permanece constante.

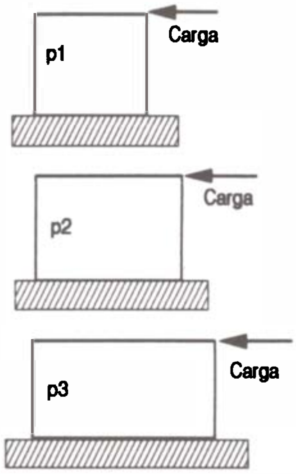

Figura 4 Ensayo de Paredes

Tabla 1 Resistencia de Paredes ante Cargas Laterales

Espécimen	Resistencia por m de ancho (N/m)	Mecanismo de Falla
P1	4,600	Volteo de la pared y separación estera-tarrajeo
P2	4,100	Fisura diagonal y separación estera-tarrajeo
P3	3,900	Fisura horizontal y separación estera-tarrajeo

Ensayo de un Módulo de Quincha

Se ensayó un módulo de quincha (Fig. 5) de 4 x 4 en planta y alturas de 2.40 y 2.80. Todos los paneles fueron de 2.40 m del altura, por lo que fue necesario un elemento reticular de madera para lograr la pendiente del techo. El techo del módulo tuvo un peso de aproximadamente 80 Kg/m². El espesor de todas las paredes fue de aproximadamente 0.10 m. Los objetivos del ensayo eran (1) desarrollar modelos que permitan estimar la respuesta, (2) investigar si el techo trabaja como un diafragma rígido y (3) estudiar el comportamiento global y de detalles de la construcción. El espécimen fue sometido a tres corridas con diferentes aceleraciones máximas del sismo. El sismo usado fue el registrado en Lima en 1970.

La falla ocurrió cuando el desplazamiento máximo (nivel del techo) alcanzó un valor equivalente al 0.5% de la altura del módulo. La falla se debió al desprendimiento del barro de la estera, lo cual constituye un punto crítico del sistema. La falla fue frágil, reduciéndose instantáneamente la resistencia a un 50% de la inicial. No hubieron daños de importancia en las paredes transversales al movimiento, en parte porque el techo constituyó una restricción efectiva al desplazamiento de las paredes transversales. El amortiguamiento medido del material fue de 8 %, valor alto en comparación con otros materiales, lo cual es una ventaja debido la disipación de energía que esto permite durante un sismo.

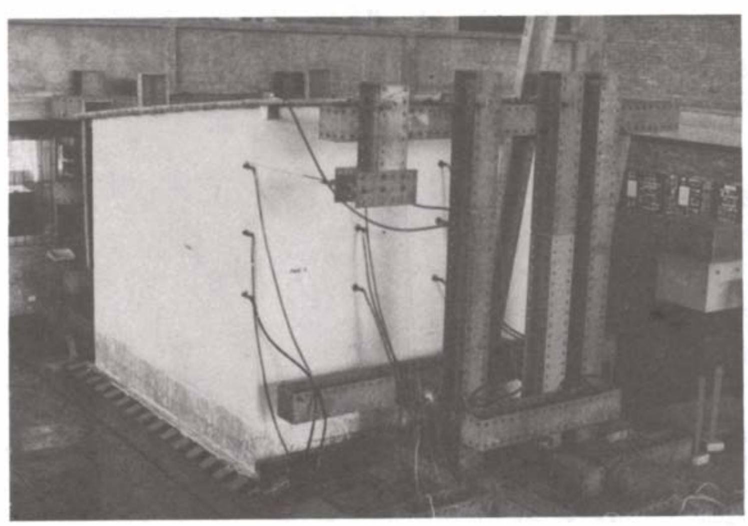

Figura 5 Ensayo del Módulo

Densidad de Paredes

Es deseable que los resultados experimentales se traduzcan en reglas simples de análisis. Dado que la resistencia de la estructura es proporcional al área de la sección transversal de las paredes (espesor x ancho), es posible expresar los requerimientos de resistencia en estos términos. El análisis sísmico se realiza corrientemente en direcciones horizontales. La Figura 6 muestra como ejemplo la planta del módulo ensayado y definiéndose dos direcciones, longitudinal y transversal.

Con el término *densidad de paredes* nos referiremos al área de paredes dividida por el área techada. Podemos calcular, entonces una densidad de paredes en la dirección longitudinal y otra en la dirección transversal.

Por ejemplo, para el módulo ensayado (Fig. 6), considerando la dirección longitudinal, tenemos dos paredes de 4 m cada una. El área de paredes es 2 x 4m x 0.10m = 0.80 m^2 en esta dirección. Siendo el área techada 16 m,^{2} la densidad de paredes es 0.80 m^2/16 m^2= 0.05 ó el 5%. Con esta densidad de paredes, el módulo resistió sismos muy severos cuya probabilidad de ocurrencia es muy remota.

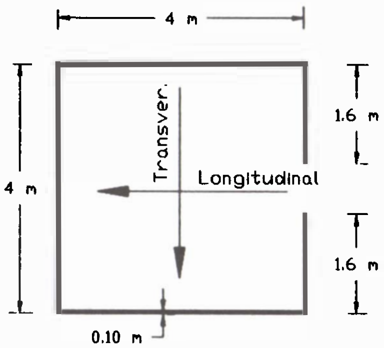

Figura 6 Direcciones para el Análisis

En base a los resultados experimentales y análisis posteriores (1) se pudo concluir que una densidad del orden de solo un 2.5%, en cada dirección transversal y longitudinal, sería suficiente para resistir sismos con una aceleración pico del 20% de la gravedad, aceleración de diseño usada en el Perú. Se determinó (1) que de este valor, una cuarta parte debería consistir en paneles sísmicos, de manera de garantizar la seguridad en caso de un sismo muy severo. Estos valores son aplicables siempre y cuando los pesos unitarios de los componentes sean semejantes a los usados en este estudio, es decir, techos de 80 Kg/m^2 y paredes de 100 Kg/m^2.

Resumen y Conclusiones

El estudio resumido en este documento fue orientado a investigar experimental y analíticamente la respuesta sísmica de la construcción de quincha. Los ensayos incluyeron la simulación de diferentes fenómenos tales como la acción de las cargas de gravedad y los sismos. La estructura de la quincha permite el trabajo complementario de tierra y madera. El tarrajeo de tierra resiste las fuerzas laterales producidas por fenómenos tales como los terremotos, mientras la madera resiste el peso de la edificación. Desafortunadamente, la caña teniendo una gran resistencia no cumple una función estructural. Los resultados experimentales demostraron que para edificaciones de 1 y 2 pisos, las cargas de gravedad no son normalmente críticas. Los ensayos dinámicos del módulo y los ensayos de paredes con cargas laterales permitieron apreciar que el punto crítico del sistema es la adherencia barro-estera, produciéndose una falla frágil en la cual se reduce bruscamente la resistencia. Por este motivo se ha propuesto el uso de paneles sísmicos como una medida adicional de seguridad. La forma de verificar la seguridad sísmica de la construcción propuesta es en términos de la densidad de paredes, establecida como un 2.5% del área techada en cada dirección de análisis.

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ABSTRACT

This paper synthesizes research on seismic interventions carried out on religious monuments in the historic center of Quito over the last two years. This study addresses structural diagnosis, analysis and evaluation of established methods for reinforcement and consolidation of structures. It briefly describes two case studies.

The structural intervention was aimed at restoring the rubble-work, which had deteriorated due to earthquakes, by using materials and technology that were consistent with the original construction.

KEYWORDS

"HISTORIC CENTER OF QUITO", "STRUCTURAL INTERVENTION", "EARTHQUAKE", "SEISMIC INTERVENTION", "ADOBE".

LA ARQUITECTURA DE QUITO FRENTE A LOS SISMOS.

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Objetivo

Sintetizar las experiencias obtenidas en el manejo de técnicas de conservación y reforzamiento en los monumentos coloniales religiosos de Quito afectados por sismos.

Marco referencial para el estudio

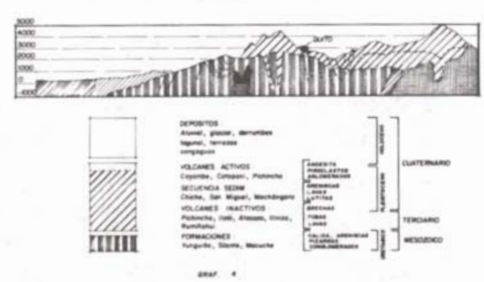
1. Aspectos geotectónicos referentes a la sismicidad regional: El Ecuador es un país andino ubicado en el continente Sud Americano (Quito, 0.180 S - 78.500 O) cuyo tectonismo está definido por los movimientos de las placas marítima de Nazca y continental Sud Americana que, al chocar, forman una zona de subducción interplaca (Ver graf. 1,2). La geomorfología andina y particularmente la de Quito, está caracterizada por un volcanismo activo y el tectonismo de las formaciones del Holoceno constituídas por depósitos aluvial, glacial, lagunal, cenizas volcánicas y secuencias sedimentarias del Pleistoceno (Ver graf. 3,4) [1].

La zona de subducción interplaca, el tectonismo andino y el volcanismo constituyen las principales áreas fuentes de los sismos (Ver graf. 5,6) [2][3].

TECTONISMO DE SUBDUCCION SUDAMERICANO

MAPA GEOLOGICO DE LA PROVINCIA DE PICHINCHA

TECTONISMO DE SUBDUCCION



2. Riesgo sísmico para monumentos históricos: El riesgo sísmico es medido en función de la máxima intensidad sísmica (Mercalli Modificada-MM) que el monumento ha resistido durante su vida útil sin llegar al colapso [4]; esta intensidad constituye el sismo de comprobación y solamente será aplicable para cada monumento cuyo período de observación sea mayor de 300 años.

MAPA DE FALLAMIENTOS DE LA PROVINCIA DE PICHINCHA

SISTEMATIZACION DE LOS FALLAMIENTOS

FUENTES DE GRAFICOS

Graf. 1 y Graf. 2: compendio de varias publicaciones sobre Tectonismo Andino.

Graf. 3 y Graf. 4: Mapa geológico de la Provincia de Pichincha. Ministerio de Energía y Minas, 1985

Graf. 5: Elaboración en base al "Mapa sismotectónico del Ecuador", INECEL y al "Mapa Hidrogoelógico de la Provincia de Pichincha", Ministerio de Energía y Minas, 1985.

Graf. 6: Estudio microsísmico del valle internadino entre Latacunga y Guayllabamba. Minard Hall, Escuela Politécnica Nacional, 1978.

* Autor a quien debe ser dirigida la correspondencia.

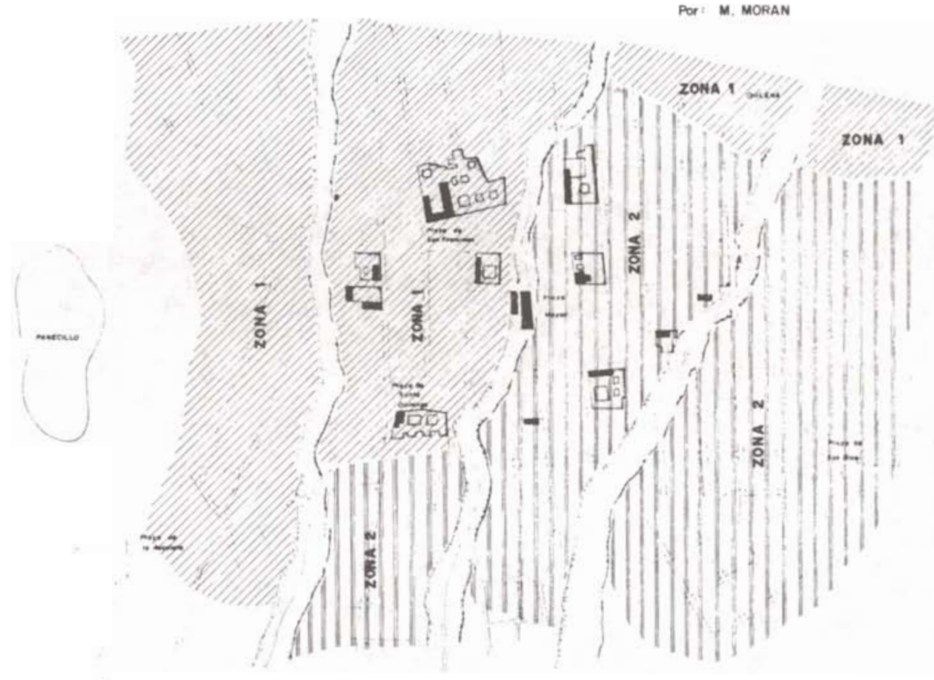
La definición del sismo de comparación en términos de la aceleración permite diseñar el reforzamiento límite adecuado para el monumento dañado por éste.

3. Microzonificación sísmica de Quito: Las condiciones dinámicas del suelo de fundación determinan otro parámetro, pues una respuesta inadecuada de la interacción suelo-estructura produce un riesgo que deberá ser moderado con una intervención estructural apropiada.

El proyecto de microzonificación sísmica para el Centro Histórico de Quito permite conocer parámetros dinámicos del suelo local (Ver graf. 7).

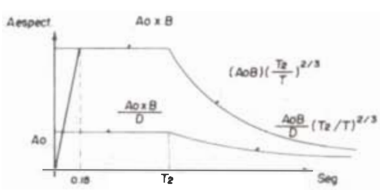
PROYECTO DE MICROZONIFICACION SISMICA PARA EL CENTRO HISTORICO DE QUITO

Por: M. MORAN



ZONA	B	T2
1	2.5	0.4
2	2.5	0.6

Para Construcciones Históricas D=2



ESPECTRO DE RESPUESTA

GRAF. 7

4. Valor arquitectónico del centro histórico de Quito: Existen dos razones que determinan el valor de Centro Histórico:

4.1 En el período colonial (1534-1810), Quito fue la ciudad de la región Norte del país menos afectada por el impacto sísmico ya que, en el mismo período, ciudades vecinas debieron ser reconstruidas o reubicadas.

4.2 La unidad espacial y formal del Centro Histórico de Quito se mantiene a lo largo de 400 años y constituye una de las pocas capitales de Latinoamérica que posee un centro de tal magnitud y características físicas.

5. Vulnerabilidad sísmica de los monumentos históricos construidos en tierra: En general, los conventos e iglesias de Quito se construyeron originalmente en adobe. Paulatinamente éstos monumentos se reconstruyeron en ladrillo. En monasterios de monjas se dieron los mismos cambios pero manteniendo el adobe en los claustros y cerramientos perimetrales.

Las construcciones históricas de adobe presentan alturas máximas de 10 metros, con muros cuyos espesores promedio son de 1.20 mt. en planta baja y 1.00 mt. en planta alta.

Las tipologías de las construcciones de adobe, que han demostrado su resistencia y estabilidad, se caracterizan por tener valores bajos, inferiores a 5 para la relación altura-espesor. Cuando esta relación tiene valores superiores a 5, su estabilidad frente a los sismos disminuye en ausencia de sistemas de arriostramiento lateral.

Lo expuesto demuestra que formas esbeltas como torres, muros sin arriostramiento y sistemas abovedados no han resistido los sismos de intensidades mayores que V (MM), lo que justifica la existencia de torres de ladrillo y reforzamiento de los muros con ladrillo, piedra y madera para mejorar su resistencia.

Reconocimiento de las tecnologías tradicionales de prevención sísmica

1. Tipologías arquitectónicas constructivas del centro histórico de Quito, procesos constructivos y materiales: El examen en muros de 17 monumentos históricos coloniales a lo largo de 22 sismos de importancia ha dado como resultado las siguientes conclusiones:

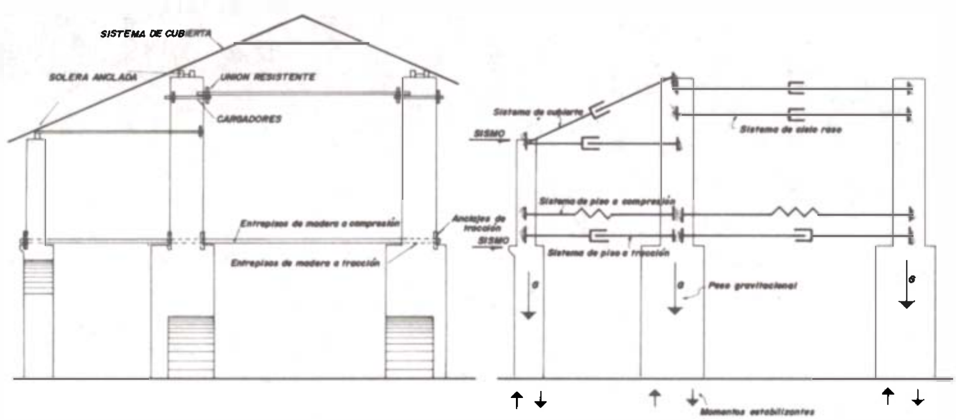
1.1 La totalidad de los monumentos religiosos conservan aún muros de adobe, muros mixtos adobe-ladrillo y solo en dos casos muros de bahareque localizados en planta alta.

1.2 En todos los casos, las cubiertas son de madera y teja con predominio de una estructura tipo rey y del tipo dos aguas adosadas.

1.3 La relación de los muros, en alto y ancho calculado por pisos, es la siguiente: en planta baja, la relación es de 3.35 y en planta alta es de 4.27, con excepción del monasterio de Santa Catalina que tiene una relación promedio de 6.0.

1.4 Las dimensiones más generalizadas para el adobe colonial van desde 44 a 46 cm. de largo por 22 y 23 cm de ancho y entre 12 y 13 cm de espesor. Los adobes producidos en el presente siglo tienen una dimensión generalizada de 40 x 20 x 10 cm. Mientras más antiguo es el adobe, mayores son las dimensiones. La pérdida de componentes orgánicos que son la paja y el estiércol es paulatina con el tiempo. Los adobes actuales producidos en la zona circundante a Quito eliminan los ingredientes orgánicos, reducen dimensiones y desmejoran su calidad.

1.5 Todos los muros estudiados son muros soportantes de adobe; se encontraron ejemplos de arcos de descarga y de bóvedas primitivas únicamente en el Hospital San Juan de Dios (Ver graf. 8,9).



SISTEMAS TRADICIONALES SISMORESISTENTES

MODELO ESTRUCTURAL PARA EL ANALISIS DE LA ESTABILIDAD.

GRAFICO No.8

Graf. 8: Propuesta de confinamiento para el Hospital "San Juan de Dios" de Quito, elaborada por Ing. Mario Morán.

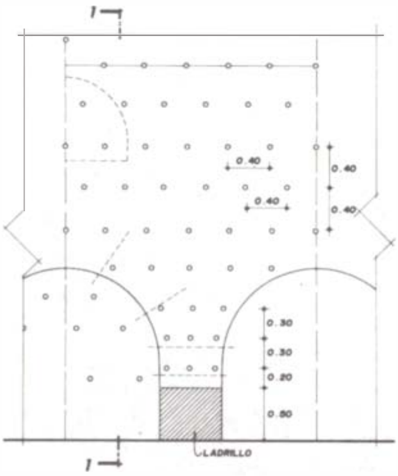
Patologías presentes en las tipologias constructivas y sistemas de comportamiento estructural en la arquitectura tradicional

Los sismos ocurridos en la colonia dieron paso a la ampliación de iglesias y conventos y a su reconstrucción parcial o total, razón por la que en la actualidad se encuentran muros mixtos con rellenos de ladrillo y piedra, que se unen con morteros de barro o de cal-arena, perdiendo su homogeneidad.

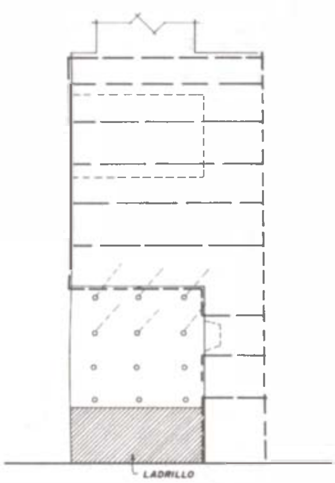
Los daños sísmicos, corresponden a una interacción entre las partes del muro y los sistemas de entrepiso y la estructura de cubierta.

Criterios de análisis estructural para construcciones en tierra solicitadas por sismos

1. Determinación del sismo de comprobación para el análisis de la edificación: Este tema constituye la principal preocupación para la determinación del nivel de intervención estructural.



ELEVACION
ESCALA: 1:40



CORTE 2 - 2
ESCALA: 1:40

GRAFICO No. 9

Hospital "San Juan de Dios" de Quito. Intervención estructural en uno de los muros de adobe.

En los estudios realizados en Quito se ha utilizado la siguiente metodología.

a. Clasificación de las intensidades sísmicas registradas que han afectado al monumento.

b. Determinación del área fuente de los sismos que han causado daños a la edificación.

c. Cálculo de la intensidad sísmica en el monumento:

$$I = 8.1871 + 0.938\, M - 1.759\, \mathrm{Ln}(R+40) \quad [5]$$

M = Magnitud (MSK)
R = Distancia hipocentral (Km)

d. Estudio crítico comparativo de las intensidades con los daños causados en el monumento, para establecer el sismo de comparación que servirá para los análisis de estabilidad.

2. Modelaje de los empujes sísmicos y cargas gravitacionales:

2.1. Empujes sísmicos: La aceleración se calcula mediante la siguiente ecuación de atenuación para Quito:

$$\mathrm{Ln}\, a = 295.214 + 0.6479\, M - 1.2151\, \mathrm{Ln}(R+40) \quad [6]$$

El período fundamental del monumento en tierra, por su gran volumen y baja altura, se lo podría considerar similar al período predominante del suelo, ya que conjuntamente con el muro constituirían un cuerpo continuo.

El empuje sísmico, como fuerza de inercia, se ha calculado utilizando las formas espectrales propuestas en el proyecto de microzonificación sísmica para el Centro Histórico [7], y la aceleración determinada para el sismo de comprobación.

2.2 Cargas gravitacionales: Constituyen el peso propio de los materiales que conforman el muro y las cargas de utilización como sistemas de entrepisos, tabiquería y cargas vivas, transmitidas como carga uniforme distribuída en toda la longitud del muro.

3. Determinación de los sistemas resistentes y definición del modelo estructural de análisis: Del análisis de las geometrías en planta y elevación del monumento y de los lineamientos de las fisuraciones producidas por los sismos, se determina en cada caso particular, los sistemas estabilizantes y sismorresistentes de la edificación los cuales son modelados estructuralmente para el análisis.

4. Métodos de análisis estructural y determinación de esfuerzos: Las características mecánicas particulares de los mampuestos y de los muros, conjuntamente con los problemas de comportamiento de la fisuración y microfisuración condicionan la necesidad de recurrir a métodos de análisis consistentes. Se ha utilizado generalmente métodos estáticos de cálculo, apoyados en la resistencia de materiales, aplicados sobre secciones unitarias de los elementos.

5. Diagnóstico y formulación de la teoría del comportamiento estructural del monumento: La comparación cuantitativa y cualitativa entre la resistencia disponible del muro y los esfuerzos mayorados, calculados por efecto de las cargas gravitacionales y sísmicas, permiten formular la teoría del comportamiento estructural sobre la cual se basa el proyecto de reforzamiento.

Desarrollo de técnicas de mejoramiento estructural

1. Técnicas de Reforzamiento: Las técnicas utilizadas son de dos tipos:

1.1. Reforzamiento de la mampostería mediante forramientos superficiales de malla metálica recubierta con mortero y anclada a la mampostería con micropilotes cortos.

1.2. Reutilización de las técnicas tradicionales de arriostramiento tales como entrepisos, llaves y soleras de madera, ayudados por tirantes de acero colocados a nivel de entrepiso y cubierta.

2. Técnicas de Consolidación: Las técnicas con finalidad de consolidación utilizadas en los monumentos consisten en la restitución de su continuidad perdida por los agrietamientos o inter-

venciones provocadas por el cambio de uso, mediante la colocación de micropilotes inyectados en la mampostería.

3. Técnicas de Mantenimiento: Los muros dañados por agentes tales como la humedad, erosión, sobreutilización o intervenciones inadecuadas fueron reparadas eliminando la causa de los daños y liberando los materiales incompatibles con la naturaleza del muro de tierra para luego recuperarlo mediante técnicas tradicionales de protección y reposición puntual de faltantes, en muchos casos aligerando las cargas muertas innecesarias y planificando un uso compatible con la resistencia y estabilidad disponibles en la obra muraria.

Casos de Intervención

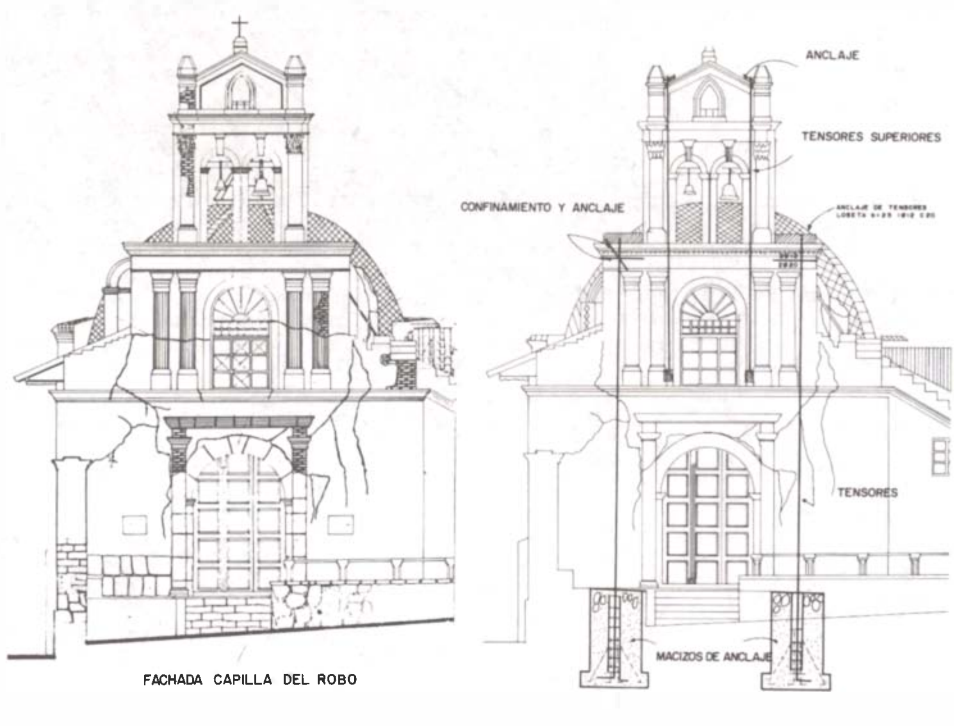
Hospital San Juan de Dios: Esta intervención se centra en el muro Sur del hospital (Ver graf. 9), destruido por efectos de envejecimiento, sobreutilización y pérdida de los mecanismos estabilizantes sismorresistentes.

Este muro de adobe data de 1564, es posiblemente el más antiguo de Quito y único en su forma, por los nichos abovedados en planta baja.

Las condiciones patológicas del muro determinaron el diseño de una intervención estructural cuyo objetivo es el "confinamiento armado" de las masas de adobe agrietadas y fisuradas para que por medio de inyecciones de morteros de terrocemento recuperen la continuidad y la resistencia adecuada para obtener una estabilidad con una seguridad consistente con la crujía de la cual el muro es parte.

El diseño de intervención se completó con propuestas de confinamiento del suelo de fundación y la reposición de los mecanismos de arriostramiento sismorresistentes originales.

Capilla del Robo: En este monumento, cobra importancia la conservación de la espadaña del frontispicio de la Capilla, por sus condiciones de gran esbeltez y la construcción mixta con dos materiales: ladrillo-adobe.(Ver graf. 10)



Graf. 10: estado actual y propuesta de reforzamiento y consolidación estructural de la Capilla del Robo.

Levantamiento realizado por el Instituto Nacional de Patrimonio Cultural.

La masa sobresaliente de la espadaña, por su esbeltez, es un elemento vulnerable al sismo; las vibraciones y desplazamientos laterales producidos afectaron al muro inferior de adobe, agrietándolo y fisurándolo con la consecuente pérdida de resistencia.

El estudio estructural demostró la necesidad de amortiguar y arriostrar la espadaña a fin de controlar la respuesta sísmica de este elemento. Para ello se diseñó un sistema de tensores verticales de arriostramiento anclados a dados de hormigón ubicados en el piso, que cumplen doble función: por una parte, controlar el volcamiento, y por otra, amortiguar las vibraciones.

La resistencia del muro de adobe fue mejorada mediante el uso de micropilotes de hierro, inyectados en la mampostería y el revestimiento de ésta con una armadura de malla metálica adherida a los micropilotes.

Conclusión

El objetivo de la intervención estructural en los edificios históricos de Quito es la de garantizar su estabilidad, sin pretender un reforzamiento más allá del resistido por el monumento a lo largo del tiempo.

La estabilidad sísmica de los monumentos coloniales construidos en tierra depende de los mecanismos de arriostramiento en madera proporcionados por los sistemas de entrepiso y cubierta.

Los testimonios actuales ponen en evidencia que formas estructurales complementarias a los muros, tales como arcos, bóvedas y cúpulas no fueron concebidas en tierra sino en otros materiales como ladrillo y pómez. Estas formas fueron importadas indistintamente desde zonas no sísmicas. Las torres han sido, a lo largo del tiempo, los elementos arquitectónicos más afectados por los movimientos sísmicos.

Los estudios de geofísica para el centro histórico de Quito han revelado parámetros dinámicos no compatibles con este tipo de edificaciones, lo que obliga a conservar los mecanismos tradicionales de protección sísmica.

La recuperación de la resistencia perdida por causas sísmicas, de envejecimiento, sobreutilización y falta de mantenimiento de los muros de adobe se ha practicado con la aplicación de técnicas de reforzamiento para otros materiales que se han adaptado para las obras de restauración en adobe.

El presente estudio posibilita el desarrollo de futuras investigaciones relacionadas con el riesgo sísmico y el comportamiento estructural de las edificaciones históricas.

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ABSTRACT

Research on antiseismic construction is increasing and finding concrete applications. It befits us to look with attention and modesty at the works bequeathed to us by architects of antiquity. They respected earthquake-resistant rules of construction. Since that time, we have invented little and forgotten much.

LE BATI ANCIEN DANS LES ZONES A RISQUES

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La leçon du passé

Avant d'avoir un certain regard sur le bâti ancien dans l'antiquité,il est important que nous distinguions les différents bâtis .Il existe des familles de bâti qui ont des caractéristiques particulières selon les matériaux qui composent les murs et par conséquent qui réagissent différemment.Pour cette raison ,il faut que nous appréhendions,les bâtis en fonctions de leur famille:le bâti en pans de bois et le bâti en pierre par exemple,réagissent différemment,vieillissent différemment,sont éventuellement sujets à des maladies différentes et l'on voit déjà là une raison pour spécifier les interventions sur un bâti selon sa nature.Il faut toujours avoir présent à l'esprit ces différentes familles de bâti.

- bâti en pierres de taille
- bâti en pans de bois
- bâti en terre crue
- bâti en terre cuite
- bâti composite

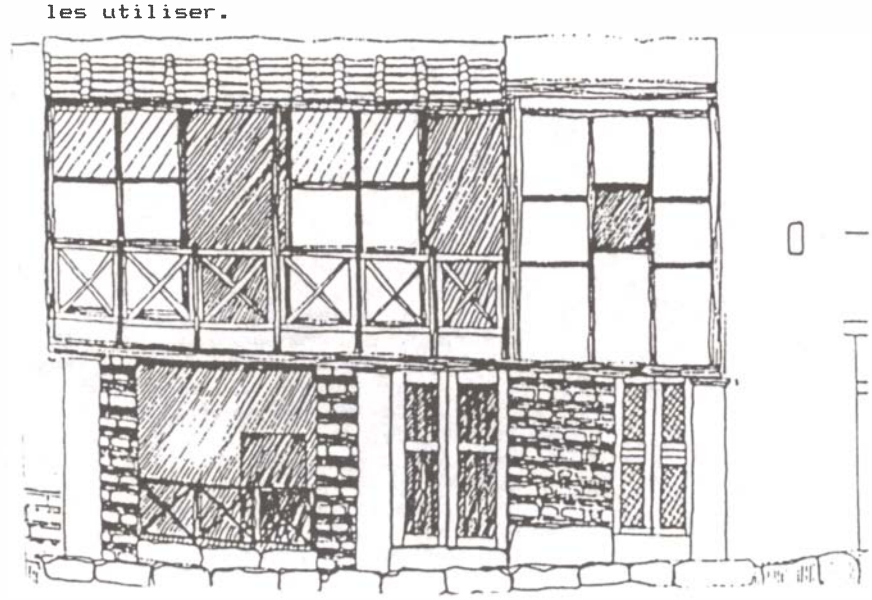
Chacune de ces familles selon qu'elle est constituée de maisons isolées ou en blocs aura des réactions qu'il nous faut essayer de comprendre.

Avoir un regard sur les techniques antiques de construction en étudiant leurs vestiges,pour un non archéologue,c'est lui permettre de mieux comprendre les techniques du bâti ancien sur lequel il travaille. Les différentes recherches nous permettent d'affirmer,peut-être avec présomption mais avec une évidente sincérité,que les témoignages du bâti simple traditionnel de l'antiquité étaient d'un niveau technologique aussi avancé que le nôtre parfois pensé de manière plus intelligente.Nous savons par la tradition écrite,le souci des anciens de construire en respectant les règles sismiques.Les travaux du professeur Bruno Helly disent maintes et maintes fois "Dieu les avaient puni car ils n'avaient pas respecté les règles."Mais quelles sont elles? Pour répondre à cette question ,il nous faut traverser les sites et les regarder avec un oeil différent.
A Pompei,nous découvrons grâce au travaux de Jean Pierre Adam les interventions de restaurations des Romains âpres le tremblement de terre de 51 ap J.C. et avant le recouvrement en 79 ap J.C.
Dans le site de Délos en Gréce ,les vestiges des soubassements nous étonnent.Par exemple,les maisons qui se trouvent à la proche périphérie de la "maison des masques"(remarquable pour ses mosaïques)nous montrent des compositions de murs fort étonnantes.Tel mur est composé de blocs de pierres importants avec ,entre eux ,de petites pierres qui par leur présence, leur nombre et leur polissage ont de toute évidence un rôle important.Ce système antisismique est comparable à celui des îles voisines comme l'île de Seriphos,les maisons du moyen-age de 1433,de même que les maisons plus récentes de 1885 sont composées avec ce même procédé,avec cependant une différence ,à savoir que les blocs sont souvent plus petits et moins soignés.Mais de toute évidence ,si une maison de 1433 nous est parvenue, cette maison a pu supporter bien des tremblements de terre.Si nous restons à Délos nous pouvons voir la encore des choses très intéressantes.Tel mur dans lequel les pierres s'imbriquent les unes dans les autres comme si elles se soudaient entre-elles.Cette composition de mur nous la retrouvons de la même maniéré dans le site ancien de la vieille théra,dans l'île de Santorin. Nous trouvons aussi dans le site de Délos des blocs de pierre de grandes longueurs .Ils liaisonnement deux murs ou angles de murs entre eux ou deux maisons entre elles. Cette technique , nous la retrouvons dans les sites des comptoirs venitiens ,mais aussi dans les maisons traditionnelles de l'île d'Andros en Grèce.Enfin au Théâtre de Délos ,les murs qui soutiennent les gradins sont pensés de manière très étonnante.Un site comme Délos est riche de remarques qu'il faudrait approfondir et rapprocher de bien d'autres sites.IL existe une foule de techniques,toutes ces techniques ne sont qu'une petite partie de ce que nous commençons à entrevoir

Les bâtis en pans de bois :c'est dans les sites archéologiques d'Herculanum ou de Pompei que nous trouvons des exemples.
Bien que Vitruve ,dans son livre ,n'accorde que peu d'intérêt aux maisons en pans de bois ,au regard des études qu'on peut mener sur les sites ,de nombreux éléments nous permettent d'affirmer que les pans de bois étaient beaucoup plus utilisé qu'on ne le pense.A Herculanum ,les pans de bois étaient très utilisés pour les étages.Notre regard se portera sur une maison que Maiuri Amadeo a fouillé la"Casa Graticio". Cette maison entièrement en pans de bois ne doit pas étonner dans un tel site antique dont les R.CH.sont en pierre.Nous allons essayer de comprendre cette maison dans sa présentation actuelle et dans les différentes réhabilitations par les archéologues .Malgré les techniques employées (le béton armé en plancher..) nous pouvons encore aujourd'hui très bien comprendre la technicité du pans de bois à l'époque romaine et la retrouver dans de nombreux bâtis anciens existants aujourd'hui.Ce qui nous permet de mieux comprendre les pièces du puzzles manquantes.Les pans de bois de cette maison étaient pensés et montés comme ceux que montaient les charpentiers du moyen-age et des époques suivantes.Ces charpentiers qui connaissaient la fabrication des navires ,savaient comment permettre à une maison en bois de se stabiliser entre deux maisons en pierres.En essayant de comprendre la maison avec Valerio Papaccio architecte du site antique nous pensons que la Casa Graticcio qui est construite entre deux maisons samnites,utilise l'espace du jardin ou des dépendances d'une de ces deux maisons, et a été construite par un des deux propriétaires soit pour être louée soit ,comme on le pense à la suite d'un tremblement de terre .Cette maison ne comporte pas de murs pignons en pans de bois .Tous les éléments porteurs (planchers)reposent sur des piliers en briques..Ceux-ci sont désolidarisés des murs des maisons voisines.Nous verrons dans la troisième partie de ce document qu"à la suite d'un tremblement de terre il ne faut jamais laisser un espace vide entre deux maisons qui ont souffert .Très souvent lorsque une maison s'est effondrée,nous,les architectes, veillons à consolider les maisons voisines en soutenant les murs pignons par des poteaux et des poutres en bois.Ici ,dans le cas de la Casa Graticcio.la même technique a été employé.Simplement l'espace vide est devenu une construction.C'est le phénomène classique de l'utilisation par les propriétaires ,des espaces vides . En comparant cette maison avec des maisons en pans de bois de Limoges ou de Toulouse ....;nous comprenons que les Romains possédaient très bien la technique du bâti en pans de bois.

Les études,les observations et tous les enseignements que nous transmet confirment la connaissance des maisons en pans de bois que nous avons pu réaliser dans le cadre de la collection des 45 ouvrages de la connaissance du Bâti Ancien d'E.D.F. Cela nous aident à comprendre l'importance du pans de bois dans les sites à hauts risques sismiques comme Pompei et Herculanum.

Nous venons de voir à travers deux sites tellement connus de l'antiquité que les bâtisseurs antiques avaient une connaissance des techniques antisismiques et qu'il savaient les utiliser.



II partie

Nous disposons de techniques antisismiques

Dans le cadre des zones sismiques ces mêmes caractéristiques apparaissent sur le bâti ancien traditionnel que nous habitons aujourd'hui et que l'on peut situer du moyen âge à nos jours.Ce bâti traditionnel,selon sa nature (en pierre ou autres) a des constantes qu'il nous faut sans cesse retrouver et approfondir.Ces techniques ne sont pas hierachisées mais trés liées aux types de bâti.

1)Le bâti en pierre
Comme nous l'avons évoqué plus haut ,les maisons grécques ont leurs murs composés de mélanges de grosses pierres et de petites pierres avec un savant agencement,les cloisons sont en pans de bois et le plafond a la particularité d'être fait de rondins de bois sur lesquels peuvent bouger des pierres plates .Le tout est recouvert d'une importante épaisseur de terre .Lors d'un tremblement de terre ,le remplacement de ces techniques par une dalle béton fragilise le bâti.Nous pouvons voir 15 à 20 ans après un certain nombre de fissures,les dalles se relevant aux extrémités.Ceci nous montre qu'il ne faut pas appliquer n'importe quelle technique mais qu'il faut rester prés des techniques du bâti ancien et des connaissance des maçons locaux qui non seulement savent les mettre en oeuvre mais aussi savent les entretenir.
Tout le monde connaît les techniques présentes dans de nombreuses régions du monde,qui consistent à renforcer les soubassements des murs comme par exemple à Annecy ou en Corse...Il existe aussi des techniques plus subtiles et qui cache une permanence constante de réhabilitation:Celle d'un des premiers projets étudiés lors du tremblement de terre en Italie en nov.1980 dans la région de la Campanie.

Cette technique consiste en une superposition de contreforts et une utilisation de l'espace entre ceux-ci .Elle est employée dans sa plus grande exubérance dans certaines îles italiennes telle que l'île de Procidea ou l' on constate en examinant de près qu'il y a une succession de contreforts qui avancent sur la mer.Ces mêmes références se retrouvent en Gréce dans l'île de Santorin,employées de façon moins importante mais on trouve aussi d'immenses contreforts qui soutiennent encore des maisons du moyen âge.
Enfin de manière plus subtile ,c'est dans l'île de Paros que l'on utilise la technique de l'arc à l'intérieur de la maison.Lorsqu'on essaye de comprendre le positionnement de cet arc ,qui se situe souvent au centre de la pièce,on constate qu'il prend appui sur un autre arc extérieur à la maison qui sert de passage couvert.Celui-ci prenant appui lui-même sur l'arc d'une autre maison.C'est ainsi qu'il existe un immense maillage d'arcs à l'intérieur comme à l'extérieur des maisons.Le non entretien de ces arcs diminue toute leur efficacité.Ce que nous admirons avec beaucoup de plaisir lorsque nous nous promenons dans les îles grecques sous les passages couverts n'est que l'inlassable volonté des habitants de créer ce maillage afin de se protéger.Ces éléments que l'on croit comme des éléments de décor sont d'une importance antisismique capitale.

Enfin les maisons de Santorin ou les rares vestiges de la région Amalfitaine en Italie sont de véritables arcs en-elles-même.Toute la toiture constitue un arc.On trouve aussi de nombreuses petites techniques pour les ouvertures ou les fenêtres,en Yougoslavie ou en gréce.

Avant d'aborder les maisons en pans de bois et comme élément de transition regardons les maisons en pierres ou autres ,dont la partie haute est en pans de bois ,telles qu'on les trouve dans le nord de la Gréce ou en Yougoslavie.A chaque niveau,les murs comportent tous les mètres des sortes d'échelles en bois posées à plat sur le mur .Ainsi la maison est striée sur toute sa hauteur par du bois qui sert de chaînage ou de liaisonnement.Cette technique se retrouve en Turquie comme l'indique Haroun Tassief dans son ouvrage comme constituant un modèle de maison rurale préconisée et figurait à ce titre sur des affiches de propagande.

Pour le pans de bois c'est en Alsace (France)que l'on remarque l'emploi de la technique du bois long qui monte sur plusieurs niveaux.Il existe dans cette région une volonté de séparer chaque niveau ,une triangulation de la toiture,et une pièce de bois "le Man"qui équerre les sabliéres avec les poteaux corniéres.La particularité de cette pièce de bois est constituée par le fait qu'elle se cheville par l'extérieur .L'observation des maisons en pans de bois nous permet de constater exactement la même technique en Turquie et en Gréce.Dans l'île de Lefkas on remarque cette technique similaire,les restaurateurs du dernier tremblement de terre ont préféré positionner des escaliers bétons devant ce type de maison,ignorant complètement le fait que les escaliers étaient construits en bois.La propriété du bois est de pouvoir se déformer.

Enfin les maisons en terre,les études à ce jour ne nous permettent pas d'affirmer encore que nous disposons des des techniques appropriées.Par contre nous savons que la particularité de ces maisons est d'avoir comme on le dit en Dauphiné "De bonnes bottes et un bon Chapeau" c'est à dire que la charpente de la toiture avec son chaînage et son poids liaisonne l'ensemble de la maison sur des bases saines.Toute fragilité des Chaînages d'angles entraîne plus souvent la chute des murs.
L'étude des technique anciennes par type de bâti a pour but non seulement d'apporter les meilleurs réponses techniques en utilisant aussi bien les techniques anciennes que les techniques modernes.Mais surtout de comprendre le comportement de ce bâti et retrouver le savoir des génération d'utilisateurs.Mais il nous faut encore beaucoup chercher et surtout analyser.

III partie
Le bâti antisismique:des réglés ,une implication...

Parmi les problèmes que nous constatons avant et après un tremblement de terre on relève un certain nombre de constantes cause de danger.
1)le problème du non entretien et des constructions abusives
2)le problème de la méconnaissance des fissures ,de l'interprétation de la lecture de celles-ci pour en évaluer le danger

En zones à risques ,le danger vient souvent du non entretien des habitations.Le non-entretien de la toiture et des murs,quelque soit le type de bâti,rend vulnérable aux secousses non seulement l'habitation mais aussi les maisons voisines.Lors des tremblements de terre ,on a pu observer des bâtis ayant souffert à cause d'un élément défectueux,une poutre mal ancrée...par exemple.Parmi les premières observations c'est telle cheminée qui peut être en danger ,telle tuile mal positionnée ,tel linteau non conforté qui peut constituer un danger.
De même la construction sauvage est un problème très grave et qui cependant s'amplifie.Un propriétaire de dernier étage qui construit une surélévation sans tenir compte de son voisinage est un réel danger.Dans le cas de Polla en Italie c'est une construction abusive qui a déstabilisé un îlot entier,alors que celui-ci avait fort bien tenu jusqu'à présent grâce à ses contreforts.
Un autre problème apparaît ,c'est le changement de nature des matériaux.Lorsque un propriétaire d'un bâti en pierre pense consolider sa maison en remplaçant une poutre bois par une poutre métallique ,ou un plancher bois par un plancher béton,les matériaux réagiront de manière différente et peuvent créer des désordres.Une des premières maisons que j'ai abordée après un tremblement de terre avait un rez-de-chaussée en pierre de taille ,le premier étage en béton ,le deuxième étage en brique.Le fils avait construit sur la maison de son père et avait réalisé une habitation pour son propre fils en brique au deuxième étage.Lors du tremblement de terre ,l'étage en béton s'est déplacé de 10 à 15cm ,quant à l'étage en brique,il fut totalement effondré.
De la même manière ,on a vu sur maisons ou la toiture avait été remplacée par une toiture en béton : des dalles (toiture) avaient bougé de plusieurs centimètres sur les murs de pierre

La lecture du bâti à travers ses fissures
Au niveau d'un îlot,la lecture des fissures nous permet de comprendre ce qui s'est passé sur le bâti.Nous devons aussi savoir si les fissures sont dangereuses ou non.

Dans le cadre des réflexions que nous pouvons faire sur le bâti ancien,le premier problème est la connaissance de ce bâti.Fort longtemps ignorée, cette connaissance n'est pas encore diffusée dans le cadre des écoles d'architecture. C'est un réel problème car on peut en voulant réhabiliter faire plus de mal que de bien.On l'a souvent constaté dans les sites archéologiques ou les restaurations ont contribué à accroître la destruction des sites.Mais la connaissance du bâti est importante car c'est dans ces zones que vivent les familles les plus pauvres,les hommes travaillant dans d'autres régions ou pays.Apporter des techniques citadines peut être totalement contradictoire pour le bâti mais aussi les vieux maçons qui sont sur place ne les connaissent pas.Il est donc important d'aider ceux qui sont sur place à mettre en oeuvre leurs propres techniques qui respectent le bâti.Il est étonnant de constater qu'une technique que l'on trouve en Yougoslavie se retrouve en gréce et dans d'autres pays.Nous devons donc avant de faire toute conclusion approfondir nos connaissances par des recherches et des échanges.
Un des principaux problèmes du bâti réside dans l'entretien de celui-ci.Tout bâti entretenu a de meilleurs chances de bien réagir.

Comme nous l'avons vu précédemment ,c'est la recherche de techniques spécifiques dans les zones sismiques qu'il nous faut approfondir souvent en étudiant les techniques de nos pères de l'antiquité à nos jours .

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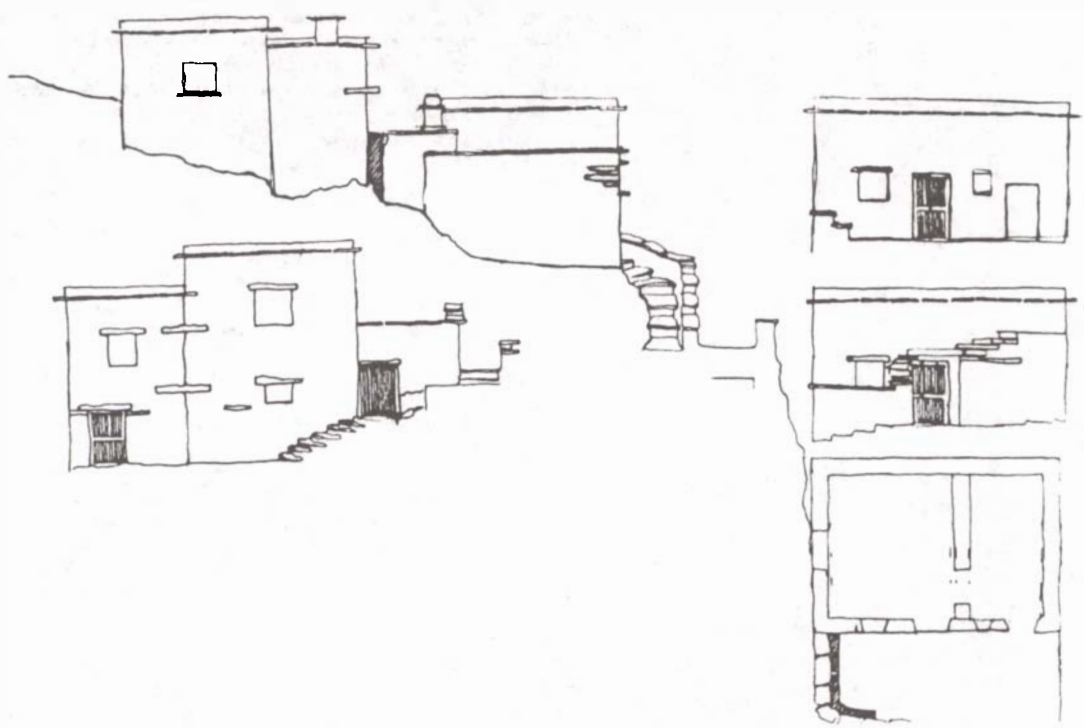

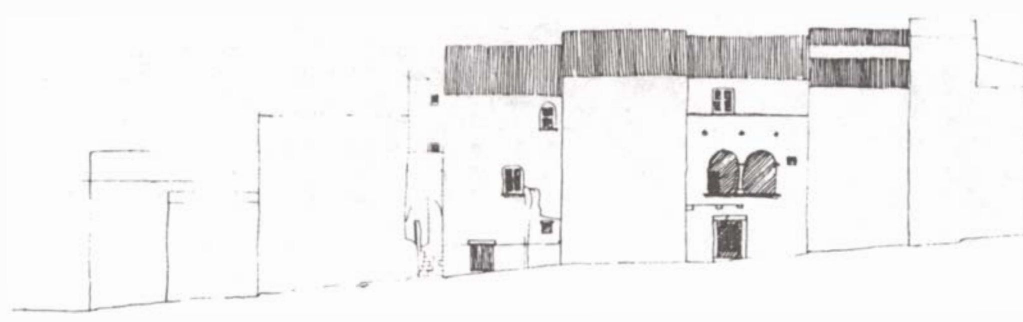

ABSTRACT:
On October 17 1983 an earthquake measuring 7.1 on the Richter scale with an epicenter in Santa Cruz County shook northern California causing massive property damage and some loss of life. Among the structures affected were the last four Hispanic Era historic adobe buildings in Santa Cruz County. Two of the four had previously been strengthened to varying extents to withstand seismic events. the Santa Cruz Mission Adobe and the two story Castro Adobe. The damage to each of the four structures is described, evaluated and major factors contributing to the damage are identified.

KEYWORDS:
Adobe, earthen architecture, seismic, earthquake, seismic mitigation

DAMAGE TO HISTORIC ADOBE BUILDINGS NEAR THE EPICENTER OF THE 1989 LOMA PRIETA EARTHQUAKE SANTA CRUZ COUNTY CA

Edna E. Kimbro
Historical: Architectural: Conservation Research

At 5:04 P.M. on October 17, 1989, an earthquake measuring 7.1 on the Richter scale occurred centered in Nisene Marks State Park in Santa Cruz County. For 15 seconds it shook Northern California causing massive property damage and some loss of life. Over the ensuing months thousands of aftershocks followed, 90 measuring over 3 on the Richter scale, 20 above 4, and 3 over 5. Santa Cruz County lies for the most part on the Pacific plate, west of the San Andreas Fault dividing the Pacific and North American plates. The Pacific plate is gradually moving north.

Only four Hispanic era historic adobe structures remain in Santa Cruz County where the twelfth Franciscan Mission was founded by Spain in 1791: the Branciforte Adobe (Ca. 1806-1818, the Bolcoff Adobe (Ca. 1839-1844), the Santa Cruz Mission Adobe (1822-1824), and the Castro Adobe (Ca. 1846-1850). Although these structures are the oldest historic buildings located in this part of zone 4, only two of the four had previously been strengthened to help withstand seismic events. All four were presumably affected by the 1906 San Francisco earthquake judging from old photographs and physical evidence of damage.

Figure 1. The Branciforte Adobe, 1987

The Branciforte Adobe

A one-story, two-room building, the Branciforte Adobe (Ca. 1806-1818), fared relatively well in the Loma Prieta earthquake of 1989. Originally it was constructed as a one-and one-half story, tile roofed one-room structure with adobe gable ends and a *tapanco* or loft above. Currently the Branciforte Adobe has woodframed additions to the west and south, a woodframed replacement south end short wall, and woodframed replacement gable over the north end adobe wall. The west long adobe wall is no longer loadbearing as the shingled roof now rests on the woodframed west wall of an addition and on the east adobe wall.

Figure 2. North end wall, Branciforte Adobe. 1990

The Branciforte Adobe is oriented with the long walls running north-south and faces east as was typical of early California adobe construction. The walls are 60 cm thick, with a height to thickness ratio of 4.5 for the long walls. The adobes measure 30 cm in width by 7.5 in depth by 60 cm in length and are laid in Flemish bond. A 30 cm interior partition wall added to the structure a 1848 features vertical wood members with specially cast adobe infill between, representing a seismically superior building technique. A similar adobe partition wall was added to the Santa Cruz Mission Adobe circa 1848 as well.

Besides the usual diagonal cracking about the door and window openings, through the wall vertical cracks occurred at the previously undamaged northeast and northwest corners of the adobe. A vertical crack widened near the northwest corner where an opening had been cut and partially filled by a cupboard.

Previous to the seismic event of October 17, 1989 the Branciforte Adobe had been rehabilitated between 1976-1986, was well maintained and in a good state of preservation. Moisture problems had been alleviated by the installation of a French drain at the north gable end and restoration of the *corredor* sheltering the east long adobe wall. These factors, together with the low height to thickness ratio and prior loss of the adobe gable, apparently contributed to the structure's performance under earthquake loads despite its proximity to the epicenter and lack of seismic strengthening.

Figure 3. The Bolcoff Adobe, 1990

The Bolcoff Adobe

Bolcoff Adobe, a one-story, two-room structure dating from ca 1839 to 1844, was the least obviously damaged by the earthquake although it is ill-maintained and in a poor state of repair.

The long walls of the Bolcoff adobe are oriented north-south with the facade facing east like the Branciforte Adobe. The walls are constructed of adobes measuring 20 cm in width, 7.5 cm in height, and 35 cm in length laid in English bond. They are 70 cm thick and the ratio of height to thickness is 3.6, well within the current code requirement of 5 in seismic zone 4.

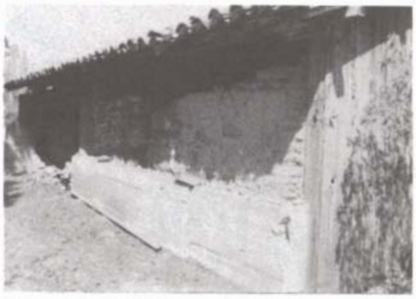

Figure 4. West elevation, The Bolcoff Adobe, 1990

The north portion of the west long wall has been replaced with formed concrete and reinforced concrete encapsulates the base of the southern wall segment extending about a meter up the wall. The south end short wall has been replaced with woodframing which supports the heavy barrel tiled roof at that end. The roof plate rests on concrete corner buttresses at the north end and at the midpoint of the east long wall; the adobe walls do not carry the load.

Mudstone foundations extend over a meter deep into the alluvial soil of the former stream bed of Wilder Creek. Ground level inside and out of the structure has been lowered over time about 30 cm exposing portions of the footings. Above the stone foundations excessive moisture has resulted in considerable erosion of the wall face, undermining the east wall near its base.

Effects of the October 17, 1989 earthquake on the Bolcoff Adobe were not devastating as might have been expected given the building's condition. A pre-existing vertical crack widened in the east wall and diagonal cracking was observed in the north end wall. There, high in the gable portion of the wall, an unframed opening suffered the loss of some adobes near the apex and the opening itself was displaced to the west. The most dramatic effects occurred in places where portions of the deteriorated adobe wall surfaces fell away exposing the darker interior of the mud bricks.

The moderate nature of the damage to the Bolcoff Adobe is attributed to stability resulting from the low height to thickness ratio of the walls, the small number of openings and the fact that the weight of the roof is not borne by the walls. The location of the Bolcoff Adobe farthest from the epicenter may have been a factor in favor of its continued survival.

Figure 5. The Santa Cruz Mission Adobe, 1990

Figure 6. Southwest corner, the Santa Cruz Mission Adobe, 1990

The Santa Cruz Mission Adobe

The Santa Cruz Mission Adobe, a one-and one-half story seven-room structure was completed in 1824 for Indian neophyte quarters at the mission. On October 17, 1989 the building was undergoing restoration and had recently been retrofitted with a horizontal concrete bond or ring beam connecting the historical outer walls with the newly reconstructed adobe cross walls. Also, a new plywood sheathed roof well anchored to the bond beam had been constructed awaiting installation of roof tiles.

The Santa Cruz Mission Adobe is atypically oriented with its long walls running east-west and the reconstructed short walls aligned north-south. The walls are constructed of adobes 20 cm wide by 7.5 cm and 42.50 cm in length laid in English bond. They are 82.5 cm thick with a height to thickness ratio of 2.66 for the long walls. The reconstructed short walls suffered the greater damage, cracking diagonally with cracks forming "X" configurations in the wall expanses and cracking diagonally at the top of openings. What initially appeared to be out-of-plane displacement turned out to be poor workmanship in the construction of the walls, the product of failure to align the courses vertically.

At the west end or short wall, a pre-existing vertical crack which had been repaired with Portland cement stucco in 1966 widened and deepened, extending through the wall at the corner. At the same corner a wide vertical crack opened in the south long wall, leaving an essentially freestanding column of adobe which toppled in an aftershock, cracking the bond beam on the west side. The upper portion of the west short end wall moved outward horizontally to the west beneath the bond beam leaning more than 10 cm from vertical. The lower portion of the wall suffered some out-of-plane damage with loss of stones from the foundation.

Factors contributing to the instability of the west end include: 1) failure to properly repair the existing vertical crack at the corner; 2) a later door cut into the west wall west face close to the corner; 3) unstable foundation conditions not completely remedied; 4) recent archaeological excavations very near the wall; and 5) lack of vertical anchorage of the bond beam to the wall.

The gables confined between the ring beam and roof framing suffered little damage. Some original mission period mud plaster with Native American Graffiti located high on a short gable wall survived more or less intact. Also intact is a mud plastered surface decorated by Indian neophytes on the interior of the long south adobe wall. This surface was painstakingly re-adhered to the adobe wall by Constance Silver and Nan Rosenthal in 1987.

The long walls aligned perpendicular to the primary north-south direction of the earthquake motion were comparatively little affected by the earthquake. Predictably, they suffered narrow diagonal shear cracks at both existing and recently filled in door and window openings. Narrow, near vertical cracks appeared on the exterior of the walls marking the intersections with newly reconstructed interior crosswalls. The original perimeter walls exhibit noticeably better workmanship in their construction with deep footings extending well over a meter below grade and mudstone rubble masonry reaching high above grade as well. They have been kept dry and roofed, and have been little affected by basal erosion.

The response of the Santa Cruz Mission Adobe to the earthquake may have been improved by the recent removal of a unoriginal second story. That factor together with the installation of a ring beam, the low height to thickness ratio of the walls, the reconstruction of multiple cross walls and the rigid roof diaphragm, contributed to the building's survival with only moderate damage.

Figure 7. The Castro Adobe, 1990

Figure 8. Damage from cocina ridge beam, the Castro Adobe, 1990

The Castro Adobe

The Castro Adobe, ca 1846-1850, the only two-story historic adobe structure in the county, is located less than 5 miles from the epicenter of the Loma Prieta earthquake. The walls of both stories are a uniform 70 cm thick and the height-to-thickness ratio of the long walls is just over 3, calculating each story separately. The adobes, 35 cm wide by 7.5 in height by 70 cm in length, are laid in heading bond on shallow mud-mortared cobble foundations about a third of a meter deep. They are made of dark subsoil with straw, while the mortar is light topsoil with considerable straw admixed.

The building is oriented typically with long walls running north-south penetrated by numerous openings. The doors and windows are symmetrically disposed and aligned one above the other. The large columns of masonry between openings cracked diagonally forming large "X" shapes. There are but two adobe cross walls on the lower floor and none above. The second story is essentially one large room 9 by 24 m.

North of the two story block, a one-story adobe *cocina*, or kitchen, was constructed against the north wall with an oversized opening in the east long wall. Within the last 30 years the roof of the *cocina* was altered in seismically unsound ways. That is, the roof rested directly on the east long wall but was raised about 10 cm above the west long wall bearing on narrow adobe infill between short studs and was not anchored to either side wall. During the earthquake, the roof's massive laminated ridge beam rammed a hole into the midpoint of the two-story north wall and cracked it vertically through the wall. The roof moved as a unit about 15 cm north thrusting out the west long wall and producing a vertical crack at the northwest corner over 10 cm wide. The north gable end wall of the *cocina* suffered major out-of-plane damage about a meter from the base. Finally, a tiny pre-existing vertical crack through the north gable end wall, where a corbel was inserted in the 1950s, widened about 10 cm. With aftershocks, the northwest corner and part of the north end wall became a freestanding column of adobe leaning outward.

Following the 1906 earthquake, the Castro Adobe had been fitted with wall anchors at the first floor plate level; these performed well in 1989 preventing the collapse of the second floor. Also, a wooden tie beam had been embedded in the north wall penetrating the east and west long walls at the midpoint of the second floor. In the 1950s, the historic roofing system was replaced by trusses and the spongy second floor suspended from the bottom chords by steel rods through the floor joists.

In 1987, evidence of settlement of the south end of the building prompted installation of a concrete grade beam to stabilize the south gable end wall *in situ*, leaning more than 10 cm from vertical at the apex. Wide welded steel straps were added extending about half way around the structure at the top of the first and second stories just below the plate, to anchor long walls. On October 17, 1989, the upper portion of the south gable end wall collapsed outward, taking the steel strap down with it. A wide vertical crack opened in the south wall at the southwest corner and a hairline crack opened at the southeast corner. A diagonal crack (which had been repaired with expanded metal lath on the exterior) widened in the west long wall at a doorway; other cracks, similarly repaired on the interior, re-opened and widened.

At the north end of the two-story block, the long walls cracked at the corners to beyond the wooden tie beam, which proved of dubious value. Both the long and short walls cracked diagonally around doors and windows. A vent, which had been opened through the wall without a header, exacerbated severe through-the-wall diagonal cracks.

Much of the damage to the Castro Adobe was predictable and partially the result of misguided interventions: "new" openings without headers, a poorly designed roof over the *cocina*, an ill-conceived tie beam, and an end wall "stabilized" out of vertical. A significant role was played by flaws inherent in the building's initial construction: shallow foundations built on fill, a paucity of cross walls, the use of heading bond, incompatible mortar, one- and two-story adjoining sections, large number of openings, their alignment, inserted load bearing corbels, etc., etc. Contributing to the building's continued existence are the uniform wall thickness of both stories, the low height-to-thickness ratio, the tying of the roof trusses to the first floor joists, the wall anchors, the north-south orientation of the long walls, the absence of any problems associated with moisture, and the overall high level of maintenance.

Conclusions

The Loma Prieta earthquake of 1989 represents only the latest demonstration of the destructiveness of seismic events to California's Spanish Colonial and Mexican earthen architectural heritage. In recent years several of the state's rare adobe monuments have been devastated by earthquakes. San Fernando Mission church was wholly destroyed in 1971; Mission San Gabriel and the Pio Pico Adobe (a State Historic Park) were severely damaged in 1987 necessitating their closure; and in 1989, the Castro Adobe joined their ranks.

None of these historic adobe structures had been effectively strengthened to withstand seismic events of appreciable magnitude, largely because of the high cost to retrofit an otherwise sound building to the standards of California's Historic Building Code. The costs are great enough that those responsible for stewardship of historical adobe resources gamble with geology. They pray the cost of earthquake repairs and necessary strengthening after a seismic event will not exceed that of pre-earthquake retrofitting. This is a gamble impossible to win in the long run and one that places California's irreplaceable historical heritage at risk.

Peru, Mexico and other Latin American nations similarly affected by "mother" earth's movements, and even more richly endowed with Spanish Colonial earthen architectural masterpieces, have assumed the leadership role in developing seismic strengthening techniques for adobe structures. These techniques have not been widely tested or accepted, much less well understood, in California. Engineers unfamiliar with them risk potential losses of historic resources in their misapplication. Clearly, existing seismic improvement techniques suitable for historic adobe buildings must be introduced in California and further research commenced to explore new methodologies.

If the status quo continues and alternative effective and affordable means to achieve seismic stabilization are not identified, tested, and adopted for use in the state, California's proud mission past will continue to be lost one piece at a time: an end wall today, a gable tomorrow, a dome, belltower or vault the next day.

ABSTRACT

This study focuses on the different applied building systems used by engineers, architects, and builders of adobe structures built immediately after the earthquakes that affected Guatemala in December 1917 and January 1918. These systems show the effort in improving the resistance and safety of these structures, considering the constant threat of further seismic activity.

Many trips were made to Guatemala City to explore the city, having selected five representative cases, describing each one's characteristics as well as the consequent effects that the structures suffered due to the 1976 earthquakes. The conclusion is that it has not been adobe, as material, that failed but the lack of adequate technology and maintenance.

Based on this conclusion, our purpose is to promote interest and knowledge of the experience of this study and that it will be useful in our work as preservationists of old buildings and planners of new housing.

KEYWORDS

ADOBE STRUCTURES, SEISMIC DAMAGE, GUATEMALA, 1917-1918

PREVENCION SISMICA EN LAS CONSTRUCCIONES DE ADOBE, EN LA CIUDAD DE GUATEMALA DESPUES DE LOS TERREMOTOS DE 1917-1918

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Introducción

Guatemala es un país que es constantemente afectado por diversos terremotos. Estos han devastado su territorio causando grandes pérdidas humanas y materiales. Entre éstas últimas, las construcciones en adobe, han sufrido severos daños.

Sin embargo, actualmente encontramos numerosos ejemplos de edificaciones en adobe que han logrado resistir satisfactoriamente esta intensa actividad sísmica. Por lo tanto, se hace necesario investigar y conocer sus características constructivas y tomarlas como experiencia para aprovecharla en la búsqueda de alternativas de restauración, consolidación y reestructuración de edificaciones antiguas, o bien, para programas de vivienda nueva de bajo costo. Además, evaluar esta experiencia constructiva, nos permitirá argumentar en relación a la idea errónea y generalizada que el adobe es un material que debe ser desechado en áreas de riesgo sísmico.

El presente es un trabajo preliminar que nos inicia en el conocimiento y comprensión de los sistemas constructivos utilizados en la arquitectura de adobe realizada en la Ciudad de Guatemala después de los terremotos de 1,917 y 1,918. (1)

Estos sistemas constructivos constituyen un testimonio histórico del avance tecnológico alcanzado en esa época, en las construcciones que preveen el riesgo sísmico, cuya eficacia, actualmente puede ser evaluada mediante las respuestas de comportamiento estructural observadas en estas edificaciones, después del terremoto de 1976. (2)

No existe investigación previa que haya tratado este tema. Por lo tanto este estudio ha sido elaborado con limitada información histórica y a través de observación de campo por la ciudad de Guatemala. En ésta se identificaron y observaron aquellas construcciones que muestran un sistema constructivo a base de adobe, escogiendo cinco de los casos más representativos y registrando, mediante fotografías, sus principales características constructivas.

La época de construcción de éstas edificaciones, así como los daños sufridos a causa del terremoto de 1976, fueron establecidos a través de entrevistas con los propietarios o usuarios de estos inmuebles.

Casos observados:

Caso 1

En este caso se pudieron observar las siguientes características:

Muros de adobe de 0.47 m. de espesor, que funcionan como muros portantes de carga, definiendo las crujías principales de la vivienda (3).

Los muros entre ambientes son tabiques construídos con adobe colocado de canto, de 0.15 m. de espesor, reforzados con reglas de madera y alambre espigado de hierro galvanizado, colocado en forma de retícula diagonal al muro, con intervalos de 0.30 X 0.30 m. en ambas caras del mismo.

Se utilizan varillas de acero de 1" de diámetro, uniendo los muros de carga, ancladas por medio de pernos sobre placas de metal (ver fotografía No. 1). Estos tirantes coinciden con los tabiques, quedando empotrados en el repello de una de sus paredes.

Con respecto a la volumetría, las crujías principales se encuentran conformadas por ambientes cúbicos de 4.5 X 4.5 X 4.5 m.

La cubierta a dos aguas, con pendientes de 45% aproximadamente, con estructura de madera cubierta con lámina de zinc.

La tipología es característica de las casas señoriales de la época histórica en estudio, con una planta en forma de E con dos patios interiores, uno inmediato al área de zaguán (área de vestíbulo inmediata al ingreso principal), y el otro patio, ubicado en la parte posterior de la vivienda inmediato al área del comedor (espacio que sirve de división entre ambos patios), donde se encuentra ubicada el área de servicio, conformada por los cuartos de servidumbre, la cocina y la pila o lavadero. Como área de transición entre los patios y los ambientes interiores, se encuentra el pórtico o peristilo que sirve de área de circulación y vestíbulo entre tales espacios.

Condición de la estructura después del terremoto de 1976

Se puede observar que la vivienda resistió aceptablemente el terremoto de 1976. Los daños sufridos, tales como grietas y desprendimientos de material en las cabezas de los muros y en los acabados, fueron reparados inmediatamente. Actualmente, sufre deterioro por falta de adecuado mantenimiento.

Caso 2:

En este caso se pudieron observar las siguientes características:

Muros de adobe en el exterior de la vivienda, reforzados con alambre de hierro galvanizado, colocados en forma de retícula diagonal al muro, a intervalos de 0.25 X 0.25 m. Estos muros de adobe, se encuentran apoyados sobre un muro de ladrillos de mayor espesor, que se levanta a una altura aproximada de 0.70 m. sobre el nivel exterior del suelo (ver fotografía No. 2).

Los tabiques interiores, son muros livianos, construídos con un sistema especial, consistente en una estructura de parales de madera colocados cada 0.30 m. Estos se encuentran cubiertos utilizando dos sistemas: a) machiembre de madera; b) malla metálica cubierta con mezcla, repello y blanqueado, dejando vacío el interior del muro.

La volumetría se encuentra conformada a base de espacios cúbicos de 4 X 4 X 4 m., con una cubierta de dos aguas con pendientes de 45%, y lámina de zinc sobre estructura de madera.

La tipología en este caso, varía con respecto a la acostumbrada en este período post-terremotos 1917-18, ya que presenta asimetría en la volumetría. Además, cuenta con los dos patios interiores circundados por el pórtico o peristilo y posee un jardín exterior, que sirve de transición entre la vivienda y la banqueta y calle pública.

Condición de la estructura después del terremoto de 1976

Se pudo apreciar que los muros no presentan grietas, sino únicamente desprendimientos de material de acabados. El problema actual es una absoluta falta de mantenimiento.

Caso 3

La construcción de este caso, es una vivienda popular ubicada en una zona periférica de la ciudad y presenta las siguientes características:

Muros exteriores de adobe, reforzados con reglas de madera en sentido horizontal y vertical. En sentido horizontal presentan una separación de 0.30 m. aproximadamente, en sentido vertical se encuentran colocadas a cada 0.90 m. aproximadamente.

La cubierta de lámina de zinc sobre estructura de madera con una pendiente de 30% a una sola agua.

La altura es relativamente baja, 2.75 m., con una volumetría en forma rectangular exteriormente. No fue posible observar su conformación interna.

El sistema constructivo utilizado en este caso es similar al utilizado en la arquitectura vernácular de las poblaciones rurales del territorio guatemalteco. Este consiste en tabiques que se construyen de palos entretejidos y barro (4).

Condición que presenta la estructura después del terremoto de 1976

Carecemos de datos exactos pero, en base a la observación de campo, pudimos apreciar la ausencia de grietas. Los daños que presenta son en la cubierta, la cual pareciera que se ha colocado provisionalmente. Además se observaron la pérdida de los acabados en la parte inferior de los muros, así como el deterioro de las piezas de madera debido a la acción de los insectos (termitas), (ver fotografía No. 3).

Caso 4

El sistema empleado en este caso corresponde a inmuebles modestos, propiedad de personas de pocos recursos económicos, localizados en zonas periféricas de la ciudad de Guatemala.

Entre sus principales características podemos mencionar las siguientes:

Los muros exteriores son de adobe colocado de canto, repellados rústicamente, reforzados con madera y alambre espigado, dispuesto sobre el muro en forma horizontal a cada 0.30 m. Este muro de adobe se asienta sobre un pequeño muro de ladrillo que se levanta aproximadamente 0.40 m. sobre el nivel de piso exterior, (ver fotografía No. 4).

Una variedad de este tipo de muro la podemos apreciar en la fotografía No. 5.

Estas viviendas tienen una volumetría exterior, en forma rectangular o cuadrada, con ambientes interiores de pequeñas dimensiones. La altura es de aproximadamente 2.75 m. y se encuentra cubierta con lámina de zinc sobre estructura de madera, a una agua, con una pendiente de 25% aproximadamente.

Condición después del terremoto de 1976

En éstos casos no se observaron grietas, sino únicamente deterioro en acabados exteriores y en las piezas de madera de refuerzo.

Caso 5

Durante el recorrido exploratorio, se pudieron observar varios ejemplos de viviendas que utilizan en sus muros el ladrillo y el adobe alternativamente, por ejemplo:

- tres hiladas de adobe y una hilada de ladrillo,
- una hilada de adobe y dos hiladas de ladrillo.

Los muros son gruesos de aproximadamente 0.45 m.

La cubierta es de lámina de zinc sobre estructura de madera, a dos aguas, con pendientes de 45%.

Su volumetría es típica de las construcciones post-terremotos 1917-1918, donde predominan las plantas arquitectónicas en forma de E y de F, con sus dos patios interiores, el pórtico o peristilo, el zaguán, etc.

Condición de estas estructuras después del terremoto de 1976

En realidad carecemos de datos suficientes que nos permitan establecer con precisión los daños que sufrieron estos inmuebles a causa de dicho terremoto. Sin embargo, los casos observados en el centro de la ciudad de Guatemala, mostraban sus muros en buena condición, con excepción del deterioro en la parte interior de sus muros, debido a la humedad.

CONCLUSIONES:

Las construcciones que después de 1917-1918 utilizaron el adobe redujeron la masividad de las edificaciones anteriores mediante la sustitución de las cubiertas de teja por cubiertas de lámina de zinc, así como los muros interiores gruesos que fueron sustituídos por tabiques delgados y livianos.

Para construir estas viviendas, se utilizaron los adelantos tecnológicos de la época (mallas, placas, pernos, alambres galvanizados y tirantes de metal) que fueron aplicados para crear nuevos sistemas constructivos que permitieran mejorar la resistencia del adobe a los esfuerzos de tensión a causa de los sismos.

La experiencia constructiva, que a grandes rasgos se encuentra contenida en este primer estudio, nos muestra que las construcciones de adobe que fueron reforzadas utilizando estos sistemas antisísmicos, resistieron aceptablemente el terremoto de 1976, y, que las edificaciones de adobe que fallaron, en su mayoría, carecían de técnicas constructivas antisísmicas complementarias o estuvieron sujetas a un deterioro previo por falta de mantenimiento.

En los casos estudiados, se puede apreciar el uso frecuente de materiales como la madera, el adobe, el ladrillo, y el metal. Estos, en diferentes combinaciones, conformaron los sistemas constructivos antisísmicos de la época.

Es necesario continuar la investigación de este tema de la tecnología constructiva antisísmica utilizada en el pasado, la cual, ignorada, constituye una valiosa fuente del conocimiento para el uso y la conservación del adobe en zonas de riesgo sísmico.

Fotografia No. 1

Fotografía No. 2

Fotografía No. 3

Fotografía No. 4

Fotografía No. 5

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NOTAS

(1) La información histórica existente sobre estos terremotos es escasa, desconociendo el grado de la magnitud que tuvieron y estimando la intensidad en 10 grados de la escala Mercalli.

(2) Se calcula que este terremoto alcanzó en la ciudad de Guatemala, una intensidad de 10 grados en la escala de Mercalli y una magnitud de 7.5 grados en la escala de Richter, calificado como devastador y provocando la muerte de 25,000 personas.
J.E. Hall Hibbits, J.A. Flores, "Medidas preventivas intervenciones de emergencia post-terremoto 1976"
(Ponencia presentada en el Seminario sobre Protección de Monumentos en áreas sísmicas, Antigua Guatemala, UNESCO, ICOMOS, OEA, CNPAG, Nov. 1979).

(3) La palabra crujía, significa: Espacio comprendido entre dos muros de carga. Cada una de las partes principales o naves en que se divide la planta del edificio. Tomado de J.R. Paniagua, Vocabularios Básico de la Arquitectura, Ed. Cátedra, 2a. Ed., Madrid 1980, 112.

(4) J.R. Tórtola, "la Vivienda de Bajareque en....." (Tesis, Fac. Arquitectura, USAC, 1986, 3).

REPAIR OF CRACKED ADOBE WALLS BY INJECTION OF MODIFIED MUD

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ABSTRACT

This paper presents the conclusions from a demonstration project designed to develop a procedure for stabilizing the walls of the Pio Pico Mansion Adobe of Whittier California damaged by earthquake.

Adobe walls of the building were cracked by the Whittier Narrows earthquake of 1987, which left portions of the walls loose and likely to become unstable in further earthquake shaking. The procedure calls for filling the cracks with mud that has been modified with lime and fly ash for strength and hardness. The mud is mixed to a fluid consistency and pumped into the cracks under pressure. The mud hardens to produce a material that has hardness, strength, and permeability characteristics similar to the adobe and that bonds to the adobe. The material, tightly filling the cracks, keys together the irregular surfaces on each side of the crack. This restores the interlocked effect of the original assembly of adobe bricks, stabilizing the wall.

KEYWORDS

Repair, cracks, seismic, stabilization, restoration, injection, earthen architecture.

Location and History of the Pio Pico Mansion Adobe

The Pio Pico Adobe is in the City of Whittier, California, about 6.4 km (four miles) from the epicenter of the Whittier Narrows Earthquake of October 1, 1987. It was originally constructed in about 1850 by Pio Pico, Governor of California, as headquarters for his "El Ranchito." It is near the San Gabriel river, and was apparently damaged by flooding in 1867-68 and again in 1884-85. In 1905, the building was intended for demolition for materials for land fill for construction of a nearby bridge. A historical society was formed to save it; the society then went on to conduct a restoration, 1907 to 1909. The State of California took ownership in 1917.

It was poorly maintained until 1944 when a second restoration was started during which walls were repaired, floors and walls were replaced, and steel beams and tie rods were embedded in walls. This work continued until 1948. A third restoration was begun in 1967 during which walls and foundations were strengthened.

The 1987 earthquake left the walls standing but extensively cracked. The Department of Parks and Recreation of the State of California is preparing for stabilization and restoration of the adobe.

Description of the Building

It is a U-shaped building divided by adobe partitions into thirteen rooms. It has a partial second story constructed of boards on sawn lumber joists supported in pockets in the wall and a lumber-framed roof supported on the tops of the walls. The walls and partitions are generally about 60 cm (two feet) thick; there is one 30 cm (one foot) thick partition. The walls are about 300 cm (ten feet) high in the first story. The gable end at the second story rises to about 240 cm (eight feet) above the second floor.

The 1987 earthquake damage consisted principally of cracks in the adobe walls. Walls in which steel beams and tie rods were found (probably from the 1944-48 restoration) were cracked, but the most seriously cracked walls appeared not to have been reinforced. There are signs of uneven settlement of the building probably related to floodings. The cracking patterns are generally vertical, indicated that, in general, the walls responded to earthquake shaking by rocking on horizontal planes, causing approximately vertical shear-related cracks near wall intersections where adjacent walls tended to restrain rocking, and approximately vertical flexural cracks at some distance from the intersections. Cracks extend through the walls and outline blocks of loose assemblies of adobe bricks and mud mortar. The rocking caused material to be eroded from the shear-related cracks as parts of the walls moved relative to one another. The cracks with horizontal orientation (on which the walls rocked) are generally closed by gravity. The generally vertical cracks vary in width from fine to as much as 2.5 cm (one inch) or more. There are many cracks in the 0.6 cm to 2.0 cm (one-quarter to three-quarter inch) width range. Some vertical cracks are at old repairs containing brick, packed soil pieces of adobe occurred, and other materials. Some vertical cracks are partly the result of separation due to failure of walls to return to their original position after rocking, but most appear to be due to loss of material eroded by the relative movement each side of the crack.

Anticipated Response to Earthquake Shaking

The response of the walls to earthquake shaking of the intensity of past earthquakes is basically stable. The walls rock safely at their base, lightly restrained by the roof and floor diaphragms. Assemblies of adobe blocks and mortar, loosened by past shaking could be further loosened and shaken from the walls by future earthquake. If the loose assemblies were stabilized into the walls, reoccurrence of the shear-related cracks and flexural cracks could be expected during future earthquakes, but overall stability of the walls is anticipated.

The Demonstration Project

The California Department of Parks and Recreation sponsored a project to develop a means of stabilization of the walls. The demonstration project was conducted by Kariotis and Associates of South Pasadena, California. It was proposed to stabilize the cracked walls by injection of a fluid material into the cracks that would harden to a soil-like fill. The material would have to have properties of hardness, strength, and permeability similar to adobe to be compatible. It should have insignificant shrinkage after placement, and it should bond to adobe.

Samples of mud grout with various additional ingredients were mixed in small batches of about 9 kg (twenty pounds). Molds for casting mud samples were made by hand-compacting moist soil around a piece of 5 cm (two-inch) diameter pipe held at the center of an approximately 15 cm (six-inch) diameter cylindrical metal can from which the top and bottom had been removed. When the pipe was removed, a cylindrical mold of soil was formed measuring 5.7 cm (two-one-quarter-inch) diameter by approximately 15 cm (six-inch-long). The cylindrical samples were cast by pouring the fluid mud into the molds. Accompanying puddle samples were also made by pouring mud onto a moist soil or visqueen sheet base. The samples were allowed to cure about four weeks. Then the cylindrical samples were sawn in cross section through the can, mud sample, and mold.

In order to have a means of controlling water content and evaluate consistency of fluid grout a simple flow-diameter test was used: grout is poured from a 5 cm (two inch) diameter by 10 cm (four inch) cylinder onto a flat, smooth, imperious surface to make a roughly circular puddle. The puddle diameter is measured; the average of two puddle widths measured perpendicular to each other, one of which is the maximum width, is called the flow diameter.

The sawn samples were observed for shrinkage, hardness, abrasion resistance, and permeability. The puddle samples were observed for breaking strength. Shrinkage was evaluated visually by noting whether a crack formed at the perimeter between the sample and the mold. Hardness, breaking strength, and abrasion resistance were evaluated qualitatively by hand, comparing the samples with the soil mold material and with adobe in the walls of the building. Permeability was observed by setting samples in a pan with shallow water, and the time required for saturation of the sample was compared with time for saturation of the adjacent soil mold.

After the small samples were evaluated, and a mix for further testing was selected, larger samples were prepared for a test of the injection procedure. To be able to evaluate the flow of the fluid mud against adobe in a crack in the wall, a test frame was constructed to mount a panel of clear acrylic plastic against the surface of an adobe wall. Because of the irregular surface of the adobe wall, the space between the plastic panel and the adobe surface varied from zero to about 5 cm (two inches). The edges of the panel were sealed with wet newspaper, and mud was injected into the space between the plastic panel and the wall. The flow of the mud into the void was observed through the plastic.

After the sample between the plastic panel and the wall had cured, the panel was removed and the sample observed for hardness, breaking strength, abrasion resistance, thickness of the leading edge of flow into thin zones of the void, and bond to the adobe.

The Injection Process

Mixed mud was transferred by buckets from a drum mixer to a holding tank with an agitator. The holding tank fed a Moino pump that forced the mud into a hose that delivered the mud to a 1.3 cm (one-half-inch) diameter nozzle that was used to inject the mud into holes in the plastic panel. The pump was capable of developing 207 kPa (30 psi) pressure.

Results of the Demonstration Project

In general the samples modified with various amounts of Portland cement and/or fly ash and lime had improved characteristics compared with the unmodified soil samples. Samples containing Portland cement tended to be harder, stronger, and less abradable than the adobe of the building. Samples modified with fly ash and lime were made that had strength and hardness comparable to adobe, but were somewhat more easily abraded than the adobe, especially at surfaces exposed to the air during curing. Twenty grit silica sand was added to some of the samples to try to improve abrasion resistance; significant improvement was not noted.

The unmodified soil samples had excessive shrinkage: cracks formed around the perimeter of the samples, and they became loose in their molds. The modified mud samples in general showed no shrinkage; except one sample developed a crack of about .005 cm (.002-inch) width. A crack in the cross section of one sample seemed to be due to the effects of sawing.

Initial shrinkage of samples in the molds was observed within the first hour after placement. In most cases the shrinkage produced a depression of about 1.3 cm (one-half inch) in the center of the top surface of the sample over the 15 cm (six-inch) depth of sample below. However, initial shrinkage of about 3.8 to 5 cm (one-an-one-half to two inches) occurred in three samples. Most of the samples were mixed in small batches in a slowly rotating drum, but the samples exhibiting a large amount of shrinkage were mixed at high speed. Since excessive initial shrinkage could be detrimental to filling cracks, slow mixing seems to be important, perhaps to avoid incorporation of excessive air into the mix. Too much water in the mix could also contribute to excessive shrinkage.

Mud injected into the void between a plastic panel and the adobe wall flowed into spaces as thin as about 0.16 cm (one-sixteenth inch). There seemed to be little resistance to horizontal flow of the grout into spaces wider than about 0.32 cm (one-eighth inch). A head of about 25 cm (ten inches) was developed above the injection nozzle.

After curing for about four weeks, the injected mud had a hardness comparable to the adjacent adobe and bonded to the adobe well enough that when peeled from the wall, a thin layer of adobe came off with the sample. The injected adobe samples had shrinkage patterns. Mixes that, indicated by excessive initial shrinkage, improper mixing procedures and water content, displayed shrinkage patterns that were judged to be excessive. The mixes that had low initial shrinkage in the cylindrical sample had a pattern of cracks on the wall of about .01 cm (.004-inch) width between uncracked pieces about 2.5 cm (one inch) in size; shrinkage indicated by this type of crack pattern was judged to be acceptable.

Permeability of the modified mud was compared with the adjacent compacted soil by placing the sample cross section in shallow water. Saturation times for soil and cured modified mud were virtually the same.

The hardened grout has a smooth texture and is a very light grayish tan, in color. The lightness of color is largely due to lime in the mix. It is not comparable in appearance to adobes or mud mortars we have encountered.

Conclusions

The mud injection procedure appears to be a good alternative to conventional crack repair methods such as rebuilding damaged walls, removing and resetting adobe blocks, or filling cracks by hand. Such methods are labor intensive and require skills that are no longer common, especially in urban areas like Southern California.

The use of lime and fly ash as mud modifiers contribute beneficially to both the fluid mud and to the hardened fill in the cracks. In the fluid state, lime gives the mud good water retention qualities that will help maintain fluidity as it flows across adobe surfaces. Fly ash, consisting principally of minute balls of glass, contributes lubrication properties to the fluid mud. Fly ash, a pozzolonic material, reacts chemically with lime to form a cementicious component that improves the strength and hardness of the crack filling material and reduces shrinkage. The resulting material, being basically a soil material, has properties compatible with the adobe it is repairing.
Since the mud was observed to flow into approximately 0.16 cm (one-sixteenth-inch-wide) voids behind the plastic panel, it should be expected that the procedure may be used to repair

cracks as small as approximately 0.32 cm (one-eighth inch) in thickness. Shrinkage was observed to be insignificant in the 5.7 cm (two-one-quarter-inch) diameter samples, indicating that repair of cracks of up to 5 cm (two inches) in width may be appropriate. The crack patterns noted in the plastic panel samples indicate that water content and mixing procedures need to be strictly controlled to minimize shrinkage of the injected material, especially when wide cracks are being repaired.

Improved abrasion resistance may be attainable if coarser sand or natural sand is used. However, use of coarse sand will greatly reduce the life of a Moino pump.

Proposed Application

It is now proposed to use the injection of modified mud to stabilize the walls of the Pio Pico Mansion. The stabilization project will be conducted using a silty sand soil. The selected soil will be tested for suitability for the project by making modified mud samples to be evaluated for shrinkage and hardness. The test program for the selected soil will be conducted by making samples using packed soil molds as was done for the demonstration project. Proposed proportions by weight for the samples are as follows:

- 60 parts soil
- 20 parts silica sand (20 grit)
- 18 parts fly ash (type F)
- 2 parts lime (type S)
- water as required for proper consistency.

Proportions by weight instead of volume are required because of the tendency of soil to bulk.

The wall cracks have been mapped and injection locations have been designated on project drawings.

To augment the resistance of the walls to shear-related cracks adjacent to wall intersections, 1.9 cm (three-quarter inch) diameter threaded fiber-glass rods, rod will be embedded to cross the intersections. The rods will be installed 5 cm (two inch) diameter holes drilled that will be pumped full of the modified mud.

Project specification are as follows:

1. The specifications for the test procedure are:

   a) Prepare packed soil molds on the ground inside a 15 cm (six-inch-diameter) by 30 cm (twelve inch) high metal cylinder of the type used for concrete compressive strength testing. The metal cylinder shall have top and bottom removed. Form the mold with a 5 cm (two-inch) diameter standard pipe at the center of the cylinder. Place moistened soil in approximately 2.5 cm (one inch) lifts around the pipe. Tamp each lift of the soil firmly with a rod of about 2.5 cm (one inch) diameter. Build mold to a depth of 30 cm (six inches). Finish the top of the mold to a level surface. Rotate and lift the pipe often to keep it free from the compacted soil surface.

   b) Mix grout in proportions and flow diameter to be tested.

   c) Pour grout into the molds in three lifts, puddling each lift with a wooden stick. Top the sample with a 12.5 cm (five-inch) diameter puddle about 2 cm (three-quarter inch) over the top of the compacted soil mold.

   d) The following day, note whether settlement of grout has occurred. If the top surface of the puddle drops below the top surface of the mold, there is excessive initial shrinkage requiring correction of mix or mixing procedure before proceeding.

   e) After twenty-eight days, saw the mold in sections without disturbing the sample and observe the packed soil-grout interface. A crack or separation between the sample and the packed soil is an indication of excessive shrinkage after set, which shall be corrected before proceeding. (Be sure that an observed crack is not caused by the sawing operation.)

f) Store sawn samples in a dry place at room temperature.

g) Fourteen days after sawing compare the hardness of the sample with the hardness of the adobe at the building by scraping with a metal tool. Acceptable hardness is equal to or slightly harder than the adobe. Adjustment of the proportion of cementitious material (fly ash and lime) to soil and sand may be required to achieve acceptable hardness. The proportion of lime to fly ash shall be kept constant.

h) An acceptable grout mix shall have the following characteristics as determined above:

- acceptable initial shrinkage
- no shrinkage after set
- acceptable hardness
- materials and procedures for making grout for the project shall be identical to those that produced the acceptable samples

2. Specifications for the injection work are:

a) Mixing
Combine the dry ingredients in a slowly rotating drum mix. Add fly ash and lime to the soil-sand mixture. Mix until uniformly blended. Add water gradually. Test flow diameter when mixture reaches a uniform consistency.

b) Mixing time
Grout not used within one hour after adding water shall be discarded.

c) Pumping
Pump grout from a mortar pump with agitating hopper that is capable of developing a pressure of 30 psi. Pump through a flexible hose to a 1.3 cm (one-half-inch) diameter thin-wall metal tube nozzle.

d) Consistency
Cracks less than 1.3 cm (one-half inch) in width: 14.6 cm (five-an-three-quarter inch) flow diameter. Cracks 3.8 cm (one-half to one inch) width: 13.3 cm (five-an-one-quarter-inch) flow diameter. Cracks 2.5 cm (one inch) and greater in width: repointing consistency; shall maintain its shape and not flow when deposited by the nozzle.

Flow diameter
The measure of fluid grout consistency shall be measured as follows:

Fill a 5 cm (two-inch) diameter by 10 cm (four-inch) high cylinder with grout. Pour the grout from the cylinder from a height of 15 cm (six inches) onto a smooth plastic sheet on a flat surface to form an approximately circular sample. Measure the width of the sample on two perpendicular axes, one of which shall be the maximum width of the sample. The flow diameter should be taken as the average of the two widths.

e) Preparation of cracks

1. Expose the full length of the crack to be injected. Remove plaster and other obstructing materials, being careful not to disturb framing members.

2. Remove accessible loose pieces of adobe and mortar from the crack.

3. Blow dust and small particles from the cracks with compressed air.

4. Caulk cracks on both sides of wall with wet newspapers. Caulk in lengths of about 15 cm (six inches) between 1.3 cm (one-half-inch) diameter openings. Press the wet newspaper into the cracks at a depth about equal to the cracks width. Alternatively, caulk with stiff grout to which two parts Portland cement have been added. When caulk is hard, drill 1.3 cm (one-half-inch) diameter holes into the crack at 15 cm (six inches) on center. Use non-impact drilling equipment.

f) Injection
Inject each crack from one side of the wall only. Start from the bottom and inject into 1.3 cm (one-half-inch) diameter openings in sequence working up. Plug injected holes with wet newspapers. Flow of grout shall be observed from 1.3 cm (one-half-inch) diameter opening on the opposite side of the wall. If grout does not appear on the opposite side of the wall, the reason will be determined and corrected before proceeding. As grout flows from a hole on the opposite side of the wall, the hole shall be plugged with wet newspaper. Proceed with injection until the crack is filled with grout.

g) Newspaper caulking shall be left in placed until grout has set (approximately two or three days). Remove newspaper caulking before the grout hardens (approximately seven to ten days.)

h) Clean-up
Remove all hardened spills and unused grout from the site and dispose of it legally. Leave floors broom clean.

3. Specification for the threaded fiberglass rods are:

a) Fiberglass rods shall by 3/4" diameter threaded rods of glass fiber in vinylester resin; Fibrebolt as manufactured by Morrison Molded Fiber Glass Company. Nuts shall be fiberglass. Washers shall be galvanized standard cut steel washers.

b) Drill holes for 2" diameter fiberglass anchors with non-impact tools.

c) Holes for fiberglass anchors shall be drilled after cracks in the vicinity have been injected and the grout has set.

d) Injection holes for fiberglass anchors shall be 1/2" diameter and shall intercept the bottom of the hole into which the anchor is inserted.

e) Injection grout into the injection hole, filling the anchor hole and embedding the fiberglass rod in one operation. Plug the injection hole with wet newspaper. Remove the plug after grout has set and before it hardens.

<u>Further Research</u>

Walls repaired by the proposed injection process have not been subjected to in-situ testing, nor to actual earthquake shaking. A test program to evaluate how well the method actually restores the integrity of repaired walls would be an important next step. Future testing should focus on the effect the grouting process has on resistance to formation of shear-related cracks adjacent to wall intersections as well as the effectiveness on restoring the bond of loose assemblies into the wall.

ABSTRACT

The author outlines geographic features of the Peruvian landscape previously occupied by ancient civilizations that left behind a substantial legacy of structures made of earth. The 300 years of Spanish colonization added to this legacy.

This paper presents an analysis of social and economic factors bearing on the survival of these structures over the last 150 years. Five specific interventions are described and documented, with discussion of the theoretical orientation and results. Finally, the experience of restoring archeological and colonial monuments made with adobe is summarized, with the recommendation that more research is needed on the preservation of the Andean mural paintings that adorn the walls of adobe houses and churches built during the colonial period.

KEYWORDS

Earthquake damage, reconstruction, restoration, improved adobe blocks, mural paintings. history.

Fortaleza de Paramonga construida con tierra, en la costa peruana, antes de la llegada de los españoles.

Construcciones de adobe de época Inca en el sitio de Tambo Colorado, con restos de pintura de vivos colores.

"CRITERIOS Y TECNICAS DE RESTAURACION APLICADAS EN LOS MONUMENTOS DE ADOBE EN EL PERU"

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Introducción :

El Perú está situado en la parte central y occidental de América del Sur, en un territorio en el que la Cordillera Andina presenta distintos planos altitudinales, con marcadas diferencias de clima, topografía y vegetación que determinan la existencia de un litoral desértico, de valles interandinos, altiplanos y de selva tropical. Gracias a su cercanía a la línea ecuatorial, las partes altas de los Andes tienen climas benignos que han permitido su ocupación desde épocas muy antiguas.

Los grupos humanos que ocuparon ese territorio desde hace dieciocho mil años se adaptaron a sus condiciones geográficas, obteniendo el mejor provecho de sus variados ecosistemas y alcanzaron un alto grado de organización y desarrollo tecnológico.

El empleo de bloques de tierra secados al sol o tierra confinada y apisonada, constituyó el procedimiento constructivo más utilizado en el Perú antiguo y lo encontramos en la costa árida y sin lluvias, donde se combinaba la tierra con cañas y fibras o en las zonas lluviosas de la cordillera, donde existe abundante piedra que se empleaba en la cimentación de las edificaciones.

Desde 2000 años antes de Cristo se levantaron complejas edificaciones de tierra creando una arquitectura monumental expresada en pirámides truncadas, templos y conjuntos urbanos de gran calidad . Al producirse la conquista española en el siglo XVI se introdujeron cambios fundamentales en los aspectos tecnológicos y culturales, pero se continuó construyendo con adobes, por ser éste un material al que también estaban habituados los europeos, que lo seguirían utilizando durante los casi trescientos años que duró el Virreynato del Perú.

En el período que siguió a la independencia del dominio español ocurrida en la primera mitad del siglo pasado y casi hasta la década de los años cuarenta del presente siglo, el adobe continuó siendo el material básico para las edificaciones y en la actualidad todavía representa la única alternativa de bajo costo para que gran parte de la población pueda construir sus viviendas.

Las primeras intervenciones de restauración:

Como en pocos lugares del mundo en el territorio descrito florecieron numerosas civilizaciones y culturas que a través de los siglos dejaron un cuantioso legado monumental, que debería haberse conservado celosamente para convertirse en un ejemplo de la capacidad técnica y artística de las generaciones pasadas y constituir un hito de identidad para los peruanos. Sin embargo, por mucho tiempo, esa herencia del pasado fue olvidada e incomprendida sin merecer ninguna acción de protección.

En la década de 1930 a 1940 se efectúan los primeros trabajos para conservar los monumentos coloniales mediante intervenciones que denotan empirismo y falta de criterios adecuados. Por lo general se respetó poco la originalidad de los materiales y se prefirió la reconstrucción antes que la restauración. A raíz del terremoto que afectó a la capital del Perú en 1940, causando cuantiosos daños en los monumentos religiosos y en la arquitectura civil, se restauró un número importante de iglesias coloniales construídas con adobe y estructuras ligeras de caña y barro, que en su mayor parte habían sido modificadas y remodeladas en el siglo XIX. En esos trabajos la preocupación se encaminó a la recuperación de la fisonomía original de las fachadas e interiores, sacrificando la autenticidad de los testimonios en aras de reconstrucciones historicistas.

A partir de la década de los años sesenta se llevaron a cabo las primeras labores en los monumentos arqueológicos de la costa peruana encaminadas a su reconstrucción, con el objetivo de conservarlos y sobre todo de permitir que los visitantes perciban como fueron esos testimonios antes de su abandono y ruina. Los resultados fueron muy discutibles y objetados por los arqueólogos porque se efectuaron completando los materiales originales de los edificios, sin contar con las evidencias que justifiquen la reproducción de formas hipotéticas.

Iglesia Jesuíta de los Desamparados edificada en 1670, demolida en 1937.

Iglesia de La Merced en Lima, mostrando su aspecto neoclásico antes de la reconstrucción de 1939.

Aspectos de la misma Iglesia reconstruida tomando como referencia grabados y fotografías del siglo XIX.

Situación actual y tareas futuras de conservación:

Por lo general los planes y acciones estatales para conservar y recuperar el patrimonio monumental peruano, han surgido a raíz de catástrofes como los terremotos que periódicamente dejan sentir sus efectos. Así como el sismo que afectó Lima en 1940 determinó las primeras obras de restauración en las iglesias coloniales, fue a raíz del terremoto que se produjo en Cusco en 1950 que se contó con la primera misión que efectuaba la UNESCO fuera de su sede, para orientar la recuperación del conjunto monumental.

En 1970 la ciudad de Trujillo ubicada en el norte del país, fue dañada por un nuevo terremoto y para contribuir a la recuperación de sus monumentos se organizó otra misión de la UNESCO que preparó un conjunto importante de proyectos, recogiendo los criterios contemporáneos de restauración e introduciendo la modalidad del trabajo interdisciplinario. Con la creación del Instituto Nacional de Cultura en 1973 se organizaron las áreas encargadas de la conservación del patrimonio histórico y se encaminaron adecuadamente los criterios para la restauración.

En ese período se recibió una importante participación de la UNESCO para desarrollar un plan en la zona de Cusco por un período de siete años. Más adelante en el marco de un plan de desarrollo turístico que contó con fondos de un préstamo del Banco Interamericano de Desarrollo se empezaron los trabajos directos en los monumentos arqueológicos y coloniales incluyendo una amplia labor de conservación de bienes muebles.

La mayor parte de los monumentos intervenidos en esa época eran de adobe y planteaban problemas nuevos que motivaron trabajos de investigación para encontrar la tecnología apropiada, desarrollando criterios para interpretar las lesiones y establecer los procedimientos metodológicos para trabajar correctamente en ese tipo de estructuras. Los resultados fueron muy alentadores y determinaron la creación de cursos semestrales de capacitación que, a su vez, permitieron la presencia en Cusco de destacados especialistas en la materia.

Ese proceso tuvo el mérito de permitir una evolución de los conocimientos y lograr que un considerable número de técnicos y profesionales compartan conceptos comúnes con respecto a las teorías y criterios de restauración, dejando definitivamente las controvertidas ideas aceptadas hasta la década de los años sesenta.

En lo relativo a la restauración de los monumentos históricos construídos con adobe, la experiencia que se obtuvo en esos años, con los trabajos realizados en Cusco, permite resumir los siguientes principios básicos:

- En los monumentos históricos edificados con adobes, estos elementos constructivos también son testimonios de la tecnología original y son parte de la documentación histórica que debe conservarse en lo posible, por lo que la sustitución del material en forma indiscriminada o la reconstrucción son prácticas que no se pueden aceptar.

- Al reemplazar los adobes deteriorados como parte del proceso de restauración, necesariamente se debe mantener la homogeneidad, lo cual excluye el uso de adobes estabilizados.

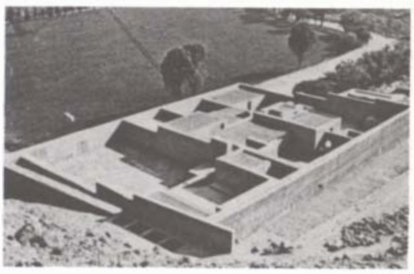
- Es recomendable que para la restauración de edificaciones de adobe que aún están en uso, como los inmuebles coloniales y republicanos, que demandan mayores requerimientos de estabilidad estructural, se utilicen adobes nuevos de dimensiones iguales a las de los originales pero fabricados con tecnología mejorada en sus características mecánicas y físicas.

- La preparación de adobes mejorados para ser utilizados en reemplazo de aquellos cuya sustitución es imprescindible, se hará mediante la selección cuidadosa de los componentes y un adecuado proceso de control de la elaboración y secado.

- Antes de emprender un trabajo de restauración es imprescindible establecer un diagnóstico para conocer los síntomas, la naturaleza y las características de las estructuras afectadas. Es por eso que además de la investigación de las lesiones y signos externos de deterioro se debe intuir cuál es la relación entre causa y efecto, vislumbrando los remedios más eficaces para anular la causa.

- Es recomendable que las soluciones de consolidación y refuerzo estructural se busquen incorporando alternativas locales y pro-

Huaca del Dragón en la costa norte, reconstruida en 1963 completando muros y relieves.



Palacio pre-Inca de Puruchuco cerca de Lima reconstruido completando arbitrariamente muros y techos.

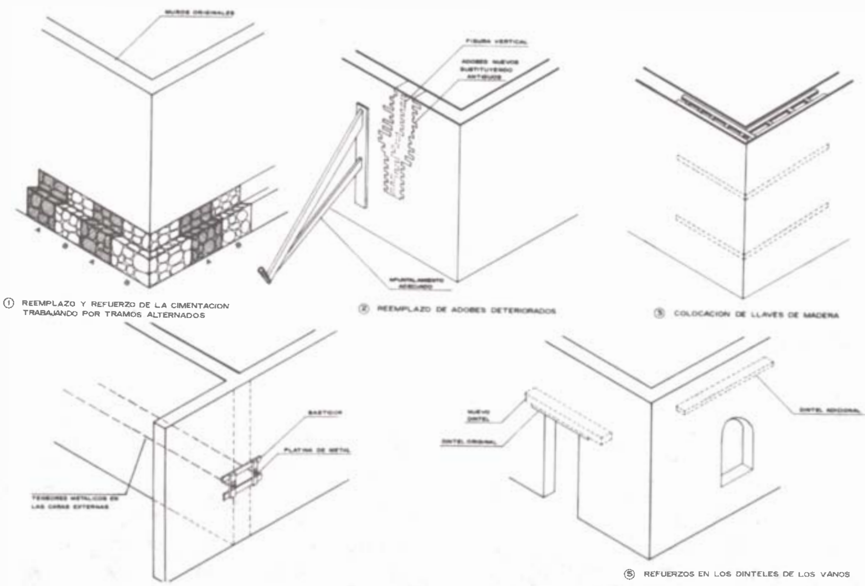
Palacio de época Inca existente en Yucay cerca de Cusco, restaurado con criterios adecuados en 1976.

Interior del mismo palacio mostrando la diferencia entre lo original y lo repuesto esquemáticamente, en base a las evidencias arqueológicas (a la derecha).

pias, prefiriendo la mano de obra y los materiales tradicionales existentes en el lugar. Excepcionalmente y cuando las condiciones lo justifiquen se podrá recurrir a técnicas y materiales industrializados.

- Aún conociendo las causas que originan los daños en los monumentos de adobe, existen casos en que el diagnóstico es complejo y no hasta el análisis matemático de los principios estructurales, sino la intuición del especialista experimentado. Como esos especialistas son escasos y se deben formar en la práctica, es conveniente el trabajo de equipo con la participación del arquitecto restaurador.

- Por último es fundamental tener en cuenta que no se puede participar en un proyecto y menos en una obra de restauración, sino se conoce a fondo qué son y por qué tienen valor las edificaciones antiguas. La formación y capacitación especializada en lo conceptual y práctico, es indispensable.



Por lo general en los monumentos que se intervinieron en la zona de Cusco y otros lugares del país desde 1975, se adoptaron las recomendaciones antes mencionadas, consiguiendo resultados satisfactorios, ejecutando los trabajos a partir del refuerzo de la cimentación, la consolidación de los muros sustituyendo puntualmente los elementos dañados, la colocación de "llaves" de madera para reforzar el encuentro de muros y la adición de dinteles mejorados en los vanos.

Sin embargo, la restauración de edificaciones antiguas construídas con adobes puede presentar casos de mayor complejidad, que no siempre pueden ser resueltos a base de los elementos citados, que son parte de la tecnología tradicional mejorada. En muchos casos los requerimientos para la nueva función de los inmuebles antiguos, la seguridad de los usuarios o de las colecciones museográficas, obligan a tener en cuenta soluciones que sean más seguras ante el riesgo sísmico.

Deben aceptarse, por lo tanto, alternativas que incorporen estructuras adicionales de refuerzo, de diseño especial para que sean compatibles con las normas y principios de la restauración y que permitan garantizar las construcciones con adobe en áreas sísmicas.

Se han experimentado con éxito estructuras de concreto armado o madera incorporadas a los muros de adobe mediante diseños especiales para evitar el daño del material de refuerzo sobre los adobes que en caso de sismo, tienen comportamientos diferentes.

En el caso de los monumentos pre-hispánicos construídos con adobes, que por su condición de testimonios arqueológicos no se restituyen a una función actual, los requerimientos de conservación han estado encaminados a proteger los edificios en forma decidida, aunque esto implica poner cubiertas temporales que nada tienen que ver con las originales.

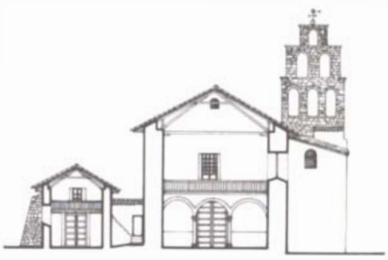
Para mejorar la resistencia de los adobes, se han introducido importantes avances técnicos, aplicando emulsiones acrílicas con lo cual se logró endurecer e impermeabilizar el material antiguo.

Friso con figuras en relieve en la ciudad pre-hispánica de Chanchán, tratados con silicato de etilo.

Un especialista de la Universidad de Turín enviado al Perú por la UNESCO probó la aplicación de un producto remineralizante, el éter de ácido silícico para reforzar los silicatos que se encuentran en la composición del barro, haciéndolo impermeable. El silicato de etilo se disuelve en alcohol y se caracteriza por tener gran capacidad reticular y por lo tanto se obtiene buena penetración en frisos y muros.

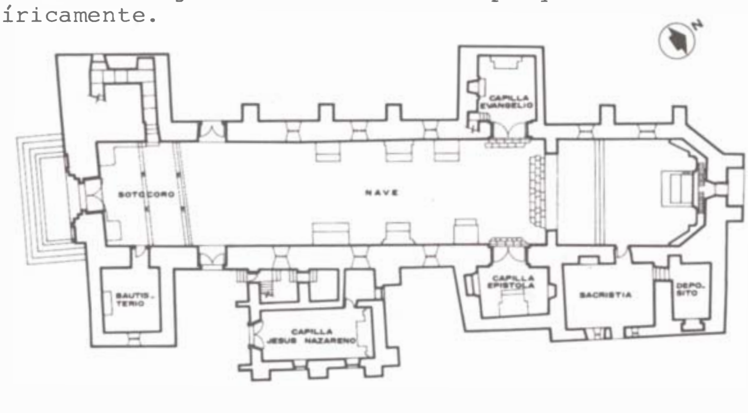
Ese producto se utilizó con éxito para preservar los adobes y morteros de barro de revestimiento de monumentos arqueológicos en la zona de Cusco y en varios sitios de la costa peruana.

Otro aspecto que empezó a cobrar importancia en la década de los años setenta, fue el de la conservación de la pintura mural asociada a las estructuras de adobe, tanto del período pre-hispánico como de la época colonial. Gracias al clima seco y árido de la costa peruana se han conservado importantes testimonios de pintura mural, en los sitios arqueológicos de Pañamarca, Garagay, Paramonga y Sechín. Lamentablemente muchas de ellas se deterioraron por haberlas dejado al descubierto o porque fueron restauradas empíricamente.



CORTE TRANSVERSAL

ELEVACION FRONTAL



PLANTA

Relevamiento de la iglesia de Oropesa, cerca de Cusco, construida al final del siglo XVI. Conserva importantes pinturas murales de varios períodos.

Más abundante es la pintura mural existente en las iglesias coloniales, en especial en las numerosas parroquias y capillas rurales situadas entre Cusco y el lago Titicaca. Encontramos allí pinturas renacentistas ejecutadas entre 1570 a 1630, con interesantes temas mitológicos, también pinturas barrocas del Siglo XVII y murales de fuerte influencia indígena pintados desde el Siglo XVIII hasta el inicio del siglo pasado.

Bautisterio de la iglesia de Oropesa durante el proceso de recuperación de la pintura mural del siglo XVII, cubierta con estuco.

La profusión de pinturas murales se explica por su utilización como instrumento de catequesis y por su valor didáctico para inculcar la religión cristiana a los indígenas. La existencia de esas pinturas también en casas coloniales demuestra que se trata de una expresión artística de gran aceptación y difusión.

Los estudios sobre la pintura mural son relativamente recientes, en particular, los referidos a las pinturas al temple, policromadas, que se aplican directamente sobre una base de preparación encima de los enlucidos de barro que revisten los adobes. Las restauraciones que se emprendieron en Cusco a mediados de los años setenta, introdujeron técnicas de exploración que permitieron descubrir gran cantidad de pinturas cubiertas por capas posteriores y recuperarlas tras paciente trabajo.

Si bien se lograron buenos avances en el conocimiento de las técnicas y componentes de la pintura mural, habiéndose experimentado y probado diversos materiales y productos químicos para su consolidación, será necesario hacer un gran esfuerzo para emprender acciones dirigidas a conservar las pinturas murales, que de otro modo desaparecerán en pocos años.

La estructura social que permitía a las iglesias rurales contar con tierras de cultivo para sufragar los gastos de su cuidado y mantenimiento desapareció con la reforma agraria, quedando éstas en el más grave abandono, que está produciendo su ruina acelerada.

Dramático estado de conser vación de la mayor parte de las iglesias decoradas con pintura mural.

Lamentablemente, por ahora, solamente se está procediendo a inventariar las iglesias, capillas y casas con pintura mural, pero no existen recursos para su conservación.

Adecuada restauración y reintegración de la pintura mural en Andahuaylillas y consolidación preventiva en el Molino de los Incas, de Acomayo.

Las técnicas que pueden ser correctas para la consolidación de los muros de adobe, pueden afectar la pintura mural.

Por otro lado, los trabajos que en escaso número se vienen llevando a cabo por organismos estatales, para conservar algunas de esas iglesias, están a cargo de técnicos y personal que no tiene una idea cabal del altísimo valor de estos testimonios. Obreros de restauración que conocen el trabajo de consolidación en los muros de adobe, a falta de adecuada orientación, intervienen en muros pintados de la misma forma como lo hacen en paramentos sin pintura, ocasionando daños irreparables.

Constituye pues, un reto para el futuro inmediato estudiar medidas de protección para las pinturas murales y métodos de intervención que se adapten a las circunstancias y no causen daños a ese tipo de expresiones pictóricas.

Lamentable intervención reciente para reparar fisuras en el muro de adobe sin respetar la pintura. A la derecha se ven los daños en la pintura al reparar la cubierta.

Es imprescindible preservar la edificación antigua para salvar la pintura mural que es parte de ella.

CONCLUSIONES:

Hemos señalado brevemente, al iniciar la ponencia, las especiales circunstancias geográficas que hicieron posible que en el Perú antiguo se den grupos humanos de "alta cultura" convirtiéndose en uno de los lugares del mundo donde se desarrollaron grandes civilizaciones. En el difícil territorio del Perú existen alrededor de 50,000 sitios arqueológicos y un número menor, pero no menos importante, de testimonios históricos de época colonial y republicana. Gran parte de ese patrimonio está en peligro de destrucción a falta de una política adecuada de difusión y conocimiento de los valores propios y a la falta de acciones de defensa y conservación.

A lo largo de los últimos 150 años de vida republicana, parte de ese importante patrimonio cultural, por lo general construído con adobe, ha sido depredado y destruido.

Salón con friso y artesonado pintados, en la casa del siglo XVII de Don Fernando de Vera, en Cusco.

Detalle de la pintura mural restaurada cuidadosamente diferenciando las partes reintegradas de las originales. La restauración, con asistencia de la UNESCO, concluyó en 1978.

Sin embargo, la experiencia reciente en el campo de la restauración de monumentos de adobe en el Perú es importante y puede ser muy util no sólo para futuras intervenciones locales, sino para quienes busquen información para emprender tareas similares, pero a su vez los restauradores de monumentos y obras de arte de este país requieren todo el apoyo y colaboración de la comunidad internacional, para preservar su patrimonio histórico.

Uno de los rubros más necesitados de acción inmediata, por su carácter singular y su gran valor histórico, es la pintura mural andina del período colonial que amerita el apoyo y el esfuerzo de instituciones y técnicos empeñados en labores similares, para evitar que prosiga su deterioro y para sentar las bases científicas de su correcta conservación.

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SEISMIC STRENGTHENING OF HISTORIC ADOBE BUILDINGS IN CALIFORNIA: AN OVERVIEW

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ABSTRACT

This paper provides an overview of modifications by the earliest adobe builders and describes present-day, more sophisticated, seismic strengthening systems. After the 1960s seismic strengthening systems were employed using a combination of grade beams, columns, and bond beams. But when the State Historical Building Code was adopted in 1976, it allowed systems that are far less destructive to historic fabric. Three examples of structural strengthening systems in historic adobes since 1975 are described. The first example documents a high-impact system (now out-moded and possibly unneccessary). The other two examples utilize systems that rely primarily on the concrete bond beam. The Santa Cruz Mission Adobe restoration (a bond beam system) was put to the test during the 1989 earthquake and performed well. The evidence in this project supports the hypothesis that a structural system consisting of a bond beam is sufficient to withstand moderate to severe earthquakes.

KEYWORDS

Seismic strengthening, retrofit, adobe preservation, historic architecture, earthquakes, California missions

Figure 1. Spanish mission locations superimposed on seismic risk map (Seismic information from BOCA National Building Code, 1987).

Running parallel with the development of adobe building in California is a history of periodic destruction by earthquakes. The use of adobe as a building material was introduced into Alta (upper) California by the Spanish Crown. The chain of Franciscan mission settlements that extend northward from Baja California are located in an area which coincides with what is today designated on the seismic risk map as Zone 4—the area of greatest damage and area closest to major earthquake faults (see fig. 1) [1]. Destruction by seismic forces was a tremendous threat to the early builders of adobe mission and ranch buildings, as the results of years of painstaking labor could be destroyed in seconds.

A great earthquake which struck in 1812 in southern California affected missions from as far south as San Diego to as far north as Mission La Purísima in central California. Fr. Luis Gil and Fr. Marcos Amestoy of Mission Santa Bárbara wrote in their annual report, "In the terrible earthquakes of December 21st and the days following, the mission was considerably damaged, necessitating a careful inspection and somewhat extensive repairs." [2] Distressed reports similar to the above are repeated over and over in the annual reports of the Franciscan fathers.

As a result of the 1812 earthquake a belfry and a roof of the stone church at Mission San Gabriel (known as San Gabriel de los Temblores) collapsed [3] and the Great Stone Church with vaulted ceilings at San Juan Capistrano was in ruins after only six years of use [4]. The adobe church at Mission San Buenaventura was damaged by earthquakes in 1800, 1808, and a new church under construction was damaged by the 1812 temblor requiring repair work and modifications to the building design [5].

In central California in 1825, an earthquake with many aftershocks battered the mission church at Mission Santa Cruz. Due to a lack of workers, it was never adequately repaired and when a major earthquake struck in 1857, the church, by then described as "in ruins," was destroyed [6]. To the north at Mission San José, a new adobe church was under construction in 1808 when an earthquake struck the San Francisco Bay Area. Because of this quake and its aftershocks, it was decided to construct a low bell tower instead of the taller one originally planned. This mission church had adobe side walls 9 m (30 ft.) high and 1.5 to 2.7 m (5 to 9 ft.) in thickness with massive buttresses. An enthusiastic French priest "improved" the simple church building by removing the buttresses and cutting tall, Gothic-influence windows. This modification no doubt contributed to the inability of the church walls to resist lateral motion when a major quake rolled through the area in 1868. The church was destroyed [7]. In the Los Angeles area, the church at Mission San Gabriel is presently closed due to damage from an earthquake in 1987.

Adaptations Developed to Withstand Earthquake Forces

The earliest adobe builders on the California coast, educated through trial and error, understood their material well enough to make the following adaptations to improve resistance to seismic forces:

- A ratio of wall thickness to wall height of 1 to 5 was typically maintained. For example, a 9 m high wall would be built 1.5 m in thickness [8].
- Openings in walls such as doors and windows were kept small and to a minimum.
- Bell towers and bell walls were often built low, not extending above the roof.
- Large stone or adobe buttresses were built to brace long walls or corners, such as at Mission La Purísima and at Mission San José church.

Figure 2. Mission San Juan Bautista, Convento Wing. View of damage after the 1906 earthquake. (Photograph from San Juan Bautista Historical Society)

After the demise of the mission system in the 1830s, many of the mission structures fell into disuse or were relegated for utilitarian purposes such as storage rooms or stables. Little interest was shown in these aging relics until after 1900 when activity which was primarily reconstruction occurred at 5 or 6 mission sites in the state [9].

On the crest of renewed interest in the restoration of historic adobes after the 1960s, architects working with structural engineers devised seismic strengthening methods to satisfy building officials and owners of the buildings. A serious drawback to the early types of structural systems which employed grade beams, vertical columns, and bond beams was their great impact upon historic fabric. However, at the time, both public officials and design professionals were understandably cautious about the safety of the public in buildings constructed of archaic materials. Case studies follow later in the article which describe early seismic strengthening systems designed by the authors' firm.

The Development of the State Historical Building Code in California

Work on formulating a code to establish acceptable safety standards, while recognizing the unique qualities of historical structures, had begun in 1963 with recommendations from the California Landmarks Advisory Committee. The Committee expressed a need to protect public health and safety with a new building code that also offered "enough flexibility to allow restoration of a historic feature while still retaining its historic integrity." The Department of Parks and Recreation working together with the Office of the State Architect developed statewide input into a draft bill which passed the legislature in 1975. The bill (SB 927, Mills) became effective January 1, 1976 [10].

When Clarence Cullimore, Jr. of the Office of the State Architect was called upon to prepare the Adobe section of the State Historical Building Code, he drew upon the experience of his father, Clarence Cullimore, Sr. The senior Cullimore, an architect practicing in Bakersfield, California, in the 1920s and 1930s, had designed and built some two hundred new adobe buildings which employed the use of the concrete bond beam (or tie or collar beam) to encircle the walls at the top. A concrete bond beam reinforced with steel reinforcing bars acts as a band to stabilize walls as it receives the weight of the roof (and seismic forces when they occur) and distributes the load evenly, passing it down through the walls. The roof structure is attached to the bond beam so that it will not be displaced during wall movement from seismic forces [11].

In addition, Cullimore, Jr. had first-hand knowledge of an early bond beam retrofit to an historical adobe in Long Beach, California—Rancho Los Cerritos—which had undergone a strong earthquake. L. T. Evans, structural engineer, had designed a bond beam retrofit for both the two-story residence and the one-story, 140 feet long wings in a remodel of the 1844 ranch house in 1931 [12]. In 1933, two years later, an earthquake measuring 6.3 on the Richter Scale spread destruction throughout the Long Beach area. The walls of many unreinforced brick buildings fell into the streets. When Clarence Cullimore, Sr. inspected the adobe structure after the quake, he was pleased to find the adobe ranch house practically unscathed. A few cracks were observed where the one-story wings had racked against the two-story section, and there was a crack over the front door. But there were virtually no cracks at all in the one-story wings and the two-story main section [13]. This "field testing" verified that walls strengthened with bond beams could indeed withstand moderate earthquakes.

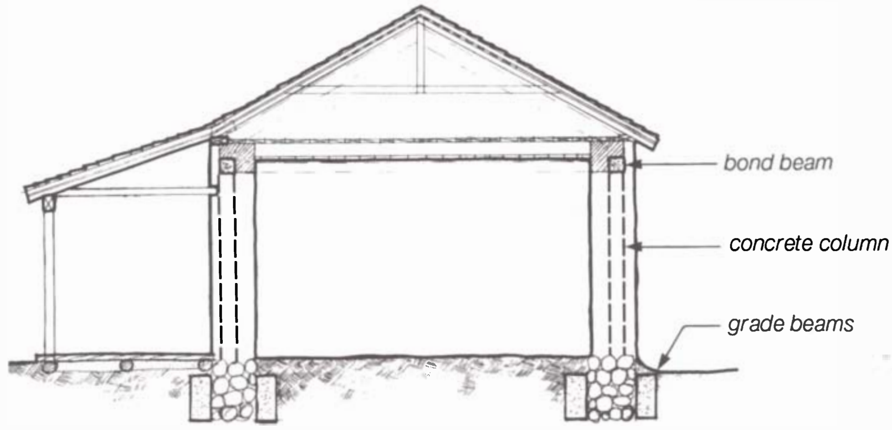

Figure 3. The Peralta Adobe, ca. 1800. Restoration and seismic strengthening completed in 1975. At this time, both vertical and horizontal concrete supports were required. Gil Sánchez, FAIA, architect.

Case Studies of Seismic Strengthening Techniques

This article will not attempt to document every strengthening method employed in the state, but will outline those techniques which are most familiar—those designed and constructed by the authors of this article.

In 1973, one of the present authors was retained by the City of San Jose to restore the Peralta Adobe, a simple one-story residence built before 1800 which is the only extant structure from the Pueblo de San José [14]. Because this was prior to the adoption of the Historical Building Code and since the Uniform Building Code of 1970 gave little or no mention of construction using unfired masonry units, structural engineers at the time could assign no value at all to the load-bearing ability of unstabilized adobe walls. Therefore, it was considered necessary to design a structural system which by itself could support the roof, with adobe walls being treated simply as infill.

For the Peralta Adobe project, Ken Yuen, structural engineer, designed a system of steel reinforced concrete grade beams, columns, and a bond beam at the roof line (see fig. 3). Adobe bricks were removed at all four corners of the building to allow for pouring the vertical concrete columns. At the base of interior and exterior walls, continuous steel-reinforced concrete footings (grade beams) were placed. At the top of the walls, a recess was excavated into the adobe material for pouring the continuous bond beam around the perimeter of the building. Vertical columns were tied into the grade beam and bond beam so that, in theory, the concrete structural elements would continue to support the roof and provide for human safety even if all the adobe walls were to collapse during an earthquake. All new structural work was concealed behind adobe and mud plaster, so that it could not be detected visually.

The disadvantage of this type of structural system, particularly for such a small building (12.8 m x 6 m), is the disturbance to the historic adobe walls. This stabilization is what Randolph Langenbach would describe as a "Vietnam approach," in which the building is practically destroyed in the name of "saving" it [15].

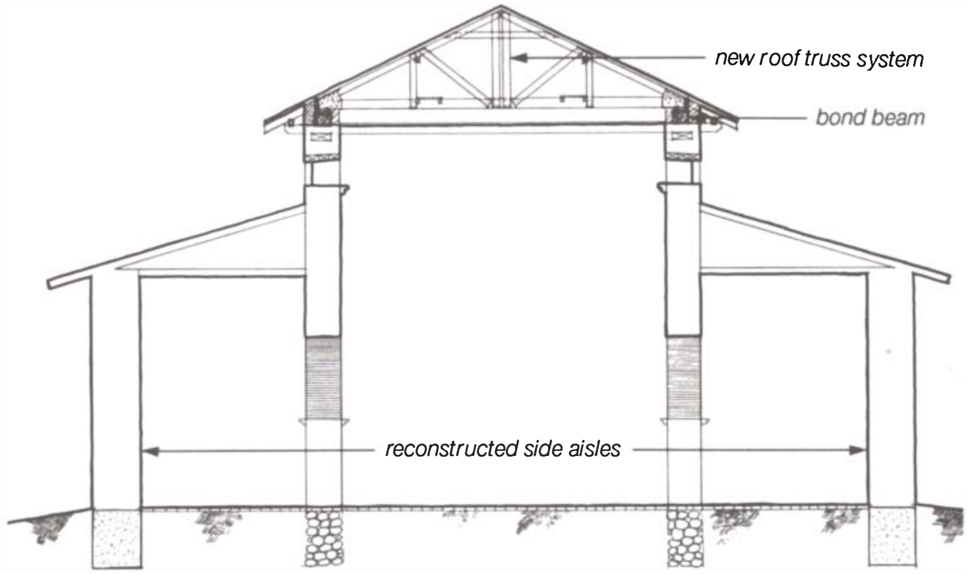

Figure 4. Mission San Juan Bautista Church, 1803-12. Restoration (supervised by Harry Downie 1975-78) included side aisle reconstruction by Michael Taylor, general contractor, and main roof reconstruction by Gil Sánchez, FAIA, architect.

Seismic Strengthening and Roof Reconstruction at Mission San Juan Bautista

This project was begun under the direction of Harry Downie and the Catholic Diocese of Monterey and consisted of reconstructing exterior church walls which had been lost due to damage in the 1906 earthquake. In the original construction the walls between the nave and side aisles were pierced with an arcade of arches, but they were soon filled in with adobe to become solid walls [16].

The first portion of the work was carried out in 1975 (by Michael Taylor, general contractor) which included installing a reinforced bond beam at the top of the newly constructed exterior walls. After the Historical Building Code came into use, unstabilized adobe walls could now be considered as load bearing walls and less structural work was deemed necessary. In addition to removing thick concrete buttresses (built after the loss of the exterior walls) and early adobes placed to fill the arched openings, epoxy was injected into each mortar joint of the arches for extra fortification [17].

The present author (G.S.) was called in to solve the problem of a sagging ceiling framing system in the church (see fig. 4). The original system designed with beams and a king post was exhibiting excessive deflection. The historic system was documented and removed and a new system was designed which was connected to the new bond beam. A new roof was installed over the church nave and side aisles and the historic roof tiles were reinstalled. The mission buildings sustained no damage during the October 17, 1989 earthquake, but for some reason which is as yet unexplained, the earthquake shocks also bypassed the little town of San Juan Bautista.

Seismic Strengthening and Restoration of Mission Santa Cruz Adobe

This adobe building owned by the State of California is the only structure remaining from the original Santa Cruz mission complex. It was built in 1822-24 to house native American families. After several years of historical research and archaeological investigation to document historic fabric and determine construction details, the present author was retained by the State to prepare construction documents for a restoration back to its mission period appearance [18].

For seismic strengthening, it was decided to install a concrete bond beam at the top of all perimeter walls and all cross walls at the plateline. The bond beam was deliberately not keyed in to the wall so that the adobe walls could flex if needed beneath the rigid beam. Cross walls that had been removed through the years were reconstructed in their historic locations and keyed in at the corners. The adobe cross walls extended upwards to the ridge of the roof and the ridge and roof beams rested on these adobe walls. To better distribute the weight of the roof beams, reinforced concrete seats were installed at the location where the beams rest on the adobe cross walls. These were not connected to the bond beam beneath them but were left "floating," supported only by adobe (see fig. 5).

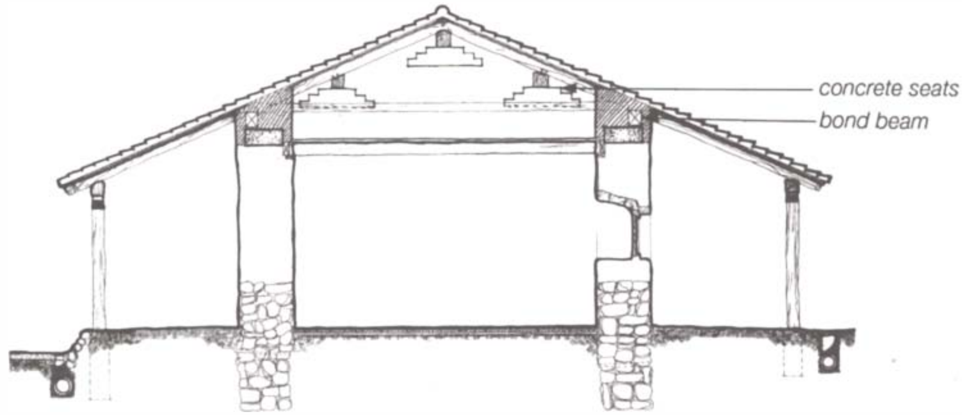

Figure 5. Mission Adobe at Santa Cruz Mission State Historic Park, 1822-24. Restoration and seismic strengthening with bond beam. Project included reconstructing four crosswalls which had been removed. Gil Sánchez, FAIA, architect.

The structural work at Mission Santa Cruz represents a system in which the adobe walls are allowed to take the full stresses of the roof load; it also recognizes the ability of the thick adobe walls to absorb energy from seismic shock. Randolph Langenbach suggests, in his descriptions of vernacular construction in Kashmir, India, that a lack of rigidity may be a positive factor to withstand earthquake forces. Speaking of historic buildings in Kashmir that have survived numerous earthquakes he states, "Because of the primitive materials and means of construction in Kashmir (masonry and timber runners combined), strength was not possible, so flexibility was necessary" [19].

The seismic strengthening work at Mission Santa Cruz was tested on October 17, 1989 when an earthquake measuring 7.1 rocked the area. Although the restoration had not been fully completed at that time, all structural reinforcing was in place including structural plywood at the roof. This adobe—the oldest building in Santa Cruz—survived the event extremely well, in contrast to many unreinforced brick buildings in the downtown area which were damaged beyond repair. As could be expected, the shorter cross walls, less flexible than the long side walls, exhibited tension cracks in the "X" pattern [20] and cross walls which were pierced with door openings were cracked more severely than solid ones. The long side walls of the mission were virtually uncracked. One end wall of the mission building was slightly displaced, moving a few inches outward from under the bond beam at the plate line, but it was determined that it could be jacked back into plumb position. Subsequent repair work consisted of injecting cracks with a mix of mud mortar and fly ash, in addition to jacking one end wall. Fiberglas rods were inserted at an angle at damaged building corners and wall intersections. Compared with the heavy losses to historic buildings in Santa Cruz from the 1989 quake, this repair work can be considered minimal.

Conclusions

Seismic activity has threatened adobe buildings since the introduction of the building type into California. In the 1970s highly rigid seismic strengthening systems with columns supporting the roof were thought to be necessary for public safety. After the Historical Building Code was adopted, seismic strengthening systems utilizing only a bond beam were encouraged. In terms of preservation, this system is much more favorable because it destroys less historic fabric. The Santa Cruz Mission Adobe, a one-story structure strengthened only by bond beams at perimeter and cross walls, was "field tested" in the October 17, 1989 earthquake and performed exceedingly well. The evidence in this example supports the hypothesis that a structural system consisting primarily of a bond beam (which allows for some wall movement) is sufficient to withstand moderate to severe earthquake shocks.

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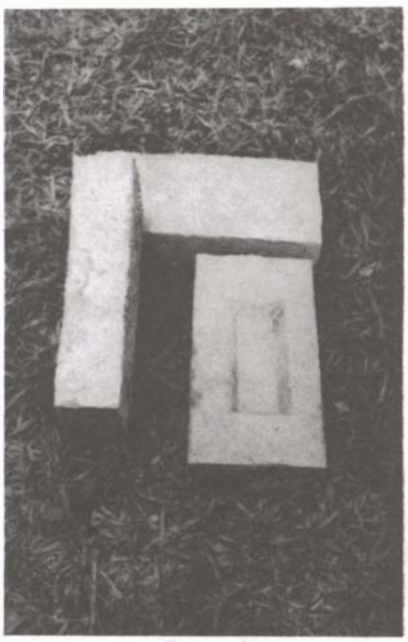
Current Field Research

ABSTRACT

This study consisted of identifying the constructive methods using adobe and a hand operated block press. The thermic characteristics of adobe were analyzed and show that using adobe walls with high thermal inertia it is possible to provide comfortable internal temperature.

KEYWORDS

Adobe, earthen architecture, Brazil.



ADOBE
Mud brick dried in the sun.

ADOBE: CONSTRUCTIVE METHOD AND THERMIC CHARACTERISTICS

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Introduction

The technologies that use earth as building material for domestic architecture have been used in Brazil from the time of their discovery until the present. The Portuguese and Africans brought their constructive methods, called adobe and pisé. By integrating them with those used by natives of Brazil, they developed another method called "taipa" or "pau-a-pique" (wattle).

Whole cities in Brazil--Ouro Preto, Diamantina, São João del Rei and others--were constructed using earth technologies. The preserved buildings of these cities indicate that with sound construction methods, careful selection of earth, together with proper protection of the walls from erosion by storms, this type of construction is capable of lasting for centuries.

These technologies were used intensively in Brazil until the coming of D. João VI, and the royal family to Rio de Janeiro. At that time, with the opening of the ports to "friendly nations," English materials such as Portland cement and glass came to be used indiscriminately.

With the advent of modern architecture and the international style, materials such as glass, steel, and concrete became symbols of "status" and modernity.

The oil and energy crisis of 1973 brought about a reevaluation of these modern materials, which are produced at a high cost of energy and resources. Engineers and architects who were interested in building comfortable houses at low cost had to look in other directions.

As a result, research began into the use of those older technologies that adapted so well to local climate and culture.

Still, the biggest problem in a country like Brazil is that people prefer imports from foreign countries because they have more "status." Earthen architectural systems are considered to be the lot of the poor who have no other choice. People do not see that building with earth is a good alternative in a country like Brazil because it is well adapted to the local climate and social conditions. Because of these misconceptions, it becomes more and more difficult to find builders who know how to select the soil and are knowledgable about the constructive method.

Adobe is one of the technologies that continues to be used because of its simplicity. The first part of this study provides an overview of the whole process, based on data obtained from many cities in northern Minas Gerais where these technologies are still used. Through personal contacts, photographs, and by participating in construction, it was possible to identify the principal elements in the adobe constructive method.

Adobe or mud brick

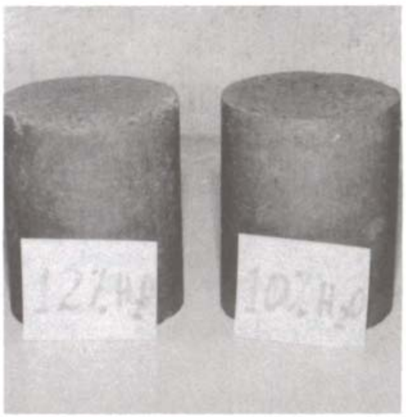
Adobe comes from the Arabic word "Adob," which means mud brick dried in the sun. It is a constructive method that uses a mud brick molded in a wooden or steel form.

It is probably the most popular earth building method used in Brazil at this present time. Its relative simplicity, which allows for "autoconstruction," and its low cost explain why it is so widely used.

Another factor is that adobe is an ecological building material. It uses natural elements and does not interfere with the environment, which is a great concern to people today. With walls of the right weakness, adobe can provide internal comfort with stabilized temperatures independent of external conditions.

Description

QUANTITY OF WATER
The best mud consistency for moulding contains 15% and 20% of water.

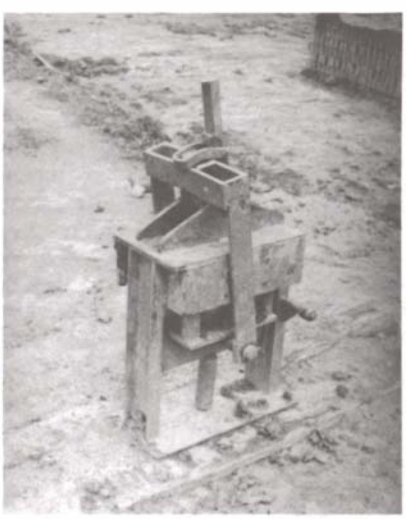


The process involves using a proper soil, with some kind of stabilizer, puddled with water. This mud can be mixed using bare feet or a mechanical process. It is necessary to test the soil in order to identify what kind of stabilizer will be used. The mud mixture is left undisturbed for 24 hours in order to attain the proper consistency. In northern Minas Gerais, the builders believe it is necessary to make adobes in "becrease moon," in order to have some cracks. It is necessary to pay attention to the quantity of water used; for adobe, the ideal consistency is 15% to 20% water by weight in its dry state. When it has attained its proper consistency, the mud is put into a wooden form, which may be dusted with a fine sand in order to facilitate removal of the finished adobes. After each adobe is finished, it is necessary to wash the form to make sure that no mud remains in the corners.

A man using a single mould can make between 200 and 500 adobes in a day. For a small house of about 60 square meters, about 3,000 adobes are required. When they come out of the moulds, the adobes must remain undisturbed for three days; then they must be left face upwards for another day in order to dry out. The adobes need to be completely dry before being used for construction. Thirty days seems to be sufficient in a normal climate without storms. It is important to cure them in the shade, not in the sun, without protection, which can cause shrinkage and consequently cracks.

Moulds

MOULDS
The adobes can be manufactured using a cinva-ram press or a wooden mould.



It is possible to use a two-brick, four-brick, or single mould. The simplest and most practical method is the single, bottomless wooden mould. It can be lined with sheet metal to allow the mould to slip easily away from the adobe when lifted. The adobe size depends on the mould; the most common has dimensions of 10 x 20 x 35 cm. The single mould has been used in a quick way that produces the same quantity of mud bricks as the multiple moulds. Special closer brick will be required for bonding, for this kind of adobes it is necessary to fix suitably shaped pieces of wood inside the mould.

Soil Selection

The proper selection of the soil is essential for a good earth building. It is necessary to investigate the kinds of soil that are available in the region. If the soil is unsuitable for the kind of construction desired, it can be mixed with others in certain proportions and used to make adobes. Simple identification of the texture and specific tests can be used to make a proper analysis and select the suitable soil. Observation of the soil texture helps to determine the soil composition. When one rubs dry soil between the fingers, the sand particles are gritty to the touch, the silt and fine particles adhere closely to the skin and have a silky feel when the sand particles are discarded. Lateritic soil, normally red and reddish-brown indicating the presence of iron (hematite) or yellow and yellowish-brown indicating the presence of limonite, often do not shrink or swell much upon wetting. They have high stabilizing qualities which are apparently connected in some way with their iron compounds and colloids. This kind of soil is desirable for earth construction. In order to manufacture adobes, it is necessary to select a soil without organic substances. Soils are usually graded into divisions according to the size of the soil particles. According to the International System of soil-texture classification:

|——CLAY——|——SILT——|——FINE SAND——|——COARSE SAND——|
0.0020(mm) 0.020(mm) 0.20(mm) 2.0(mm)

Generally, soils containing less than 20% clay are classed as sand and gravel, loamy sands, sandy loams, and loams, depending on the clay content. Soils containing from 20% to 30% clay are called clay loams and those over 30% clay are classed as clays. The silt loam and clay loam are considered suitable for adobe. But it is necessary to have the right proportion of clay to sand. Adobes made of soil with too great a proportion of clay are vulnerable to shrinkage and consequent cracking. The presence of sand in the selected soil is important because of its compression resistance and because sand is an inertial material in the presence of water.

TESTS
Before selecting the soil, it is necessary to know the percentage of clay and sand.

Analysis

A simple test can identify the percentage of clay and sand in a given soil sample. A small quantity of the selected earth is placed in a glass filling it to one third. Then measure the height that corresponds to the earth sample. Put water into the other two-thirds of the glass. Turn it over with a tampion and wash it repeatedly until the water runs clear because the clay and silt have floated off. Now measure again. Suppose the first measure was 5 cm, and the last was 3 cm. The following formula expresses the relationship:

$$\begin{matrix} 5 \text{ — } 100\% \\ 3 \text{ — } x \end{matrix} \quad \therefore \quad x = \frac{300}{5} = 60\%$$

The test shows that the percentage of sand is approximately 60%. In this way the correct percentage of sand and clay can be checked. The samples selected are triturated, put in a dish, then heated. The dried soil is weighed. Using a no. 200 U.S. sieve, the sample is washed, eliminating the clay and silt. The residue is dried again and then weighed. By comparing the measures the exact percentage of sand and clay can be determined. Generally the difference is 5% to 10% between the tests.

Soil preparation

After analysis and correct selection of the soil, it is time to prepare the mud. The soil should be reasonably free from humus or any quantity of organic material. A steel sieve can be used to make the soil homogenous and eliminate the larger stones. A shallow pit can be prepared in which the material is mixed. Based on the results of the tests described above, it may be necessary to add sand or to mix the selected soil with another kind in order to obtain the effective moisture. Other admixtures can also be used in order the stabilize the material.

Earth stabilization

The clay contained in the soil is susceptible to present differences and volume changes when mixed with water. Alternating cycles of wetting and drying causes gradual disintegration at the surface, especially at the point of contact with the water. The sand is inert and the particles do not absorb moisture, and it limits the volume changes of adobes because of the shrinkage of clay. It is possible to use admixture to stabilize the soil. Attaining the correct proportion of clay and sand is the first step. If the soil has too much sand, it is necessary to mix clay in as a binder or cementing agent, and if there is too much clay, it is necessary to add sand in order to limit the volume changes which cause shrinkage and cracks.

There are other kinds of stabilization:

1. Cementing: Using an agent such as Portland cement to reduce the volume changes of the clay.

2. The addition of fibers: straw, hair, sisal, and other similar materials can be used in order to reinforce the mud and reduce the volume changes.

3. Water-resistant stabilization: use of certain materials such as asphalt, mixing oil, to give permanent water-resistant stabilization.

4. Compaction: This increases weather resistance in machine-made blocks.

5. Lignin and tropical plants; Euphorbia lactea, with a hard elastic white film and the film of banana can be used mixed with the water that puddles the soil in order to give protection from tropical storms. It can be used in wall paints, when the plants are cut and chopped up in containers. This produces a sticky liquid which can be mixed with lime before using.

To select the proper stabilization and the quantity that is necessary it is better to make tests with different substances and different quantities before starting construction.

The quality of stabilized adobe bricks can be established recognizing testing methods:

1. General conditions: Cured mud bricks shall be reasonably true to size with parallel sides and free from excessive cracks and other defects.

STABILIZATION
The adobe bricks can be stabilized using a press.

BUILDING THE WALLS
When the adobes are completely cured, they can be used in building walls.

2. Moisture: Content of mud brick when dried and ready for use shall not be more than 4%.

3. Shrinkage cracks: Shall not be more than 1/8 inch in width and 3 inches in length.

4. Compression strength: Shall average 300 pounds or more under recognized test methods, per square inch with tolerance to 250 pounds for one brick in a test series of five.

5. Absorption: Shall average less than 2 1/2 percent of dry weight in 7 days.

6. Erosion: Bricks shall not be appreciably pited or eroded in two hours under a fine spray of water under 20 pounds of pressure.

7. Modulus of rupture: Shall average not less than from 40 to 50 pounds per square inch with tolerance to 30 pounds for one brick in a test series of five.

Mortar

Mud mortar is most commonly used for adobe wall. It is more appropriate and gives a more homogenous final result. Earth found in ant and termite houses can be used to guarantee its quality. Using some kind of stabilization, the same mix should be used as in the mud bricks. In the state of Minas Gerais, the most common mortar is 4 parts sand, one of ant or termite earth, and half of cow dung (4: 1: 1/2).

Building the Walls

Since the adobes are completely cured, they can be used in building walls. Side preparations, foundations, and provisions against dampness are requirements that must be completed before beginning the adobe walls. It is necessary to provide a special protection against moisture between the foundation and the adobe wall. Stone, brick, or wood can be used to prevent infiltration of water on the walls. The height of the foundation can be about 15 cm above the ground to protect the wall against rain and consequent erosion. When the construction is finished, protective wall coverings can be applied, mud plaster or mud mixed with a small quantity of cement and lime. If cement and lime is used, it is essential to test the quantity because a mortar that is too strong can diminish adhesion between the adobe walls and the covering.

Considerations about Earthen Homes

Certain considerations must be kept in mind when building a home of earth: views, protection against inclement weather, a suitable slope to assist drainage and provide for sewage lines. If the site is sloping, it will be an advantage, if the fall is in a direction suitable for drainage. In selecting the site it is necessary to consider the kind of soil that is available and the constructive method that best suits the particular site and building lay-out. Other local materials such as wood, stone, kiln-fired brick can be incorporated into the house design if they are available. The orientation of the house must consider the best view, the solar and wind directions as passive means of obtaining comfortable internal temperatures. In the case of a tropical country like Brazil, the orientation must, in some cases, be chosen with a preference for the dominant winds. In Araxá, with a tropical climate but high altitude (900 m), there is a thermic amplitude, which makes the solar orientation most important.

To protect the walls from weather, verandas can be used to keep out the water during rainstorms and to protect from hot sunshine during summer. The roof should be extended considerably from the walls giving complete protection from rain. Impervious masonry is desirable to a height above the finish grade which will prevent erosion from the splash of rain water. Wood or stone can be used before starting the adobe walls to reduce capillary action. A substantial foundation and footing, designed for the unit compressive soil bearing capacity is essential. Other considerations depend on the special requirements of the climate or the builder's desires.

Thermic Characteristics

Since the 1973 oil crisis, the home as energy consumer has come under consideration. Bardou (1979) states that approximately 1/3 of the total energy consumed is used by houses. Using solar energy and bioclimatic architecture, it is possible to heat or cool houses using passive methods without any further costs and providing comfortable internal temperatures. Using climate data, the designer can understand better the local meteorological parameters and orient the house adequately. Knowing the simultaneous action of temperature, sun, and wind, it is possible to have a bioclimatic conception of the project. There are two fundamental aspects to the thermal action of a building. First, it can be assumed that the external conditions are permanent and the internal temperature is constant; the thermal conductivity of the material, its resistance and conductance are considered. But, in fact, the temperature regimen is variable, and it is necessary to consider radiation and convection. In this case, the thermal characteristics that better explain the reality are heat capacity (C) and thermal inertia ( ). The heat capacity can be obtained by the specific heat of the building material c - (J/Kg C).

INTERNAL TEMPERATURES
Using adobe you can provide comfortable internal temperatures.

Calculation

For adobe the characteristic time constants found for the different wall thicknesses was: 3.47, 6.17, 18.9, and 38.59 days respectively; using brick, the characteristic time found was 2.2, 3.91, 11.98, and 24.46 days respectively.

Conclusion

Using adobe as a building material, it is important to know the constructive method, its special requirements in order to inform the design considerations, selection of the better kind of soil, simple tests to certify it, and each step of the construction. Knowing its thermal capacity, using local materials, and considering the climate, an adobe house can be constructed at low cost and comfortable internal temperatures using passive and natural means.

"Man has always had a creative instinct, which reveals itself in one way or another," and a house can express the builder himself, his personality, his dreams and determination to resolve the problem of building a shelter for himself and his family. Earth, with its universal availability, its thermal properties, low cost and ecological considerations, seems to be one of the best materials for home construction. Nonetheless, people are neglecting this method because of misconceptions. Millions of people today do not have homes. Using earth as a building material could help to solve this housing problem while revitalizing these building techniques.

Autoconstruction experience

Practical experience in using the above principals was offered in the construction of an adobe house outside of Araxá, an area of a small city in Brazil. In every aspect, from the design to construction, the architect worked with the community to take advantage of its knowledge of ambient comfort and adobe building techniques. Using CINVA RAM, a hand-made brick press was obtained. The community used the press to manufacture the adobes, but they preferred to use the single wooden form because of its simplicity.

The first difficulty in the construction was the builders' dissatisfaction with the adobe. They considered it synonymous with poverty and the lack of any other choice. After many discussions, they were convinced that they could construct a comfortable house using adobe. The steps of the construction were detailed in photographs.

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INFLUENCE DE L'HUMIDITE SUR LES PROPRIETES THERMIQUES DU MATERIAU TERRE : PROBLEMATIQUE, METROLOGIE, RESULTATS EXPERIMENTAUX.

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ABSTRACT

Considering the example of some earths used to realize "Pisé" (rammed earth), we present here experimental results concerning the influence of temperature and water-content on thermal properties of earth building material. After an introduction on the structure characterization methods of this particular granular porous material, the main mecanisms of adsorption and migration of water in earth walls are reviewed. The experimental device, a "thermal shocks probe", we use to determine the thermal parameters, heat-conductivity and heat-capacity is also described. The main conclusion we have drawn from this study is that, if the water content is not too important, the influence of temperature on heat-conductivity can be neglected and the influence of water-content on thermal parameters modelized by linear relationships. Figures and numerical values are given to estimate practically the thermal parameters of an earth buiding material in normal conditions.

KEYWORDS

EARTH BUILDING MATERIAL, POROUS MEDIUM, HEAT & MASS TRANSFER, EXPERIMENTAL METHODS, HEAT CONDUCTIVITY, STRUCTURE, CLAY, HUMIDITY.

MOTS CLES

MATERIAU TERRE, MILIEU POREUX, TRANSFERTS DE MASSE ET DE CHALEUR, METHODES EXPERIMENTALES, CONDUCTIVITE THERMIQUE, STRUCTURE, ARGILE, HUMIDITE.

Introduction

Les terres utilisables en tant que matériau de construction sont des milieux poreux granulaires dont la cohésion est assurée naturellement par une certaine proportion de phase argileuse. Quelle que soit sa composition minéralogique, celle-ci possède une structure microporeuse qui confère au matériau terre un caractère hygroscopique. Pratiquement, cela signifie que, même après la période de séchage qui suit la mise en œuvre et en l'absence de toute arrivée d'eau "parasite", une paroi en terre contient toujours une certaine quantité d'eau adsorbée par l'argile en présence de l'humidité de l'air. Sous l'effet de sollicitations climatiques, notamment thermiques, cette eau est susceptible de changer d'état (vaporisation/condensation) et/ou de migrer dans l'espace des pores, ce qui modifie évidemment le bilan thermique final. Il est indispensable d'étudier, de modéliser et de quantifier ce couplage entre transfert d'eau et transfert de chaleur dans une paroi en terre car il est clair qu'il conditionne essentiellement le confort thermique propre à ce type d'habitat. Le travail que nous présentons ici s'inscrit dans cette perspective.

Après un rappel sur la caractérisation de la structure poreuse du matériau terre et ses propriétés thermiques à l'état sec, nous passons en revue les divers phénomènes physiques qui sont à l'origine de la fixation et du transfert de l'eau dans ce matériau. Nous introduisons ensuite la notion de "paramètres thermiques apparents" d'un milieu poreux humide et nous décrivons la méthodologie de mesure de la conductivité thermique et de la capacité calorifique par "sondes à chocs thermiques" que nous utilisons. Enfin, nous présentons et nous discutons les principaux résultats expérimentaux que nous avons obtenus concernant l'influence de la température et de la teneur en eau sur les propriétés thermiques du matériau terre.

Pour cet exposé, nous avons choisi d'illustrer notre propos en considérant le cas de terres "à pisé" d'une région de France : le Dauphiné (Voir Fig. 1 et Tab. I), que nous avons plus particulièrement étudié [1,2]. Toutefois, il est clair que l'approche méthodologique que nous avons adoptée est transposable à d'autres classes de matériaux . Nous avons d'ailleurs, nous-mêmes, également travaillé sur des "torchis" ou sur des terres africaines utilisées en " façonnage direct " [1,2].

Structure et caractérisation du matériau terre, propriétés thermiques à l'état sec

Une terre crue peut être employée comme matériau de structure si, par un procédé quelconque, on peut atteindre un niveau de densité qui lui confère une résistance mécanique suffisante. Par ailleurs, un certain nombre d'identifications préliminaires (granulométrie, teneur en argile, essai "Proctor", etc…) doivent être effectuées pour savoir si une terre donnée peut effectivement être utilisée pour construire [3,4]. Quelle que soit la technique constructive finalement utilisée, la structure physique du matériau terre, en situation normale de fonctionnement, s'apparente plus à celle d'une roche poreuse qu'à celle d'un sol bien que celui-ci soit, en l'occurence, la matière première constitutive. Globalement, on pourra donc le caractériser au niveau macroscopique par des paramètres comme la densité sèche ou la porosité (Voir Tab. II). L'expérience montre que la connaissance de ces seuls paramètres suffit souvent pour prévoir correctement certaines caractéristiques fonctionnelles. Par exemple, concernant les propriétés thermiques en particulier, nous avons pu montrer que la densité sèche détermine essentiellement la conductivité thermique "à sec" (Voir Fig. 2) ce dont on peut rendre compte physiquement [1,2]. Par contre, lorsque l'on s'intéresse aux propriétés hydriques, ou à l'influence des conditions hygrothermiques sur le comportement mécanique ou thermique d'une paroi en terre, il devient absolument nécessaire de considérer d'autres facteurs structuraux.

En premier lieu, il importe de caractériser, qualitativement et quantitativement, la phase argileuse qui conditionne essentiellement les propriétés hygroscopiques (Voir § suivant). Or, la minéralogie de ce type de roches sédimentaires est singulièrement complexe [5]. Chimiquement, les argiles sont des silico-aluminates hydratés dont la structure cristalline possède la particularité d'être organisée en feuillets. Ces feuillets sont eux-mêmes constitués de couches d'atomes dont l'empilement forme deux types de motifs : octaédriques autour des atomes d'aluminium ou tétraédriques autour des atomes de silicium. Il est possible de différencier les différents groupes d'argiles suivant la séquence d'empilement des couches d'atomes dans le feuillet à laquelle correspond une distance interfoliaire caractéristique (Voir Tab. III). L'identification de ces minéraux s'effectue par cristallographie aux rayons X mais, dans les terres naturelles, de nombreux types de minéraux argileux peuvent être présents simultanément (Voir exemple Tab. I) et leur différenciation peut s'avérer difficile d'autant plus qu'ils sont susceptibles de former des composés interstratifiés (illite/montmorillonite ou montmorillonite/chlorite par exemple) et que leurs distances interfoliaires ne sont pas toujours très stables (cas des smectites). De plus, il est souvent impossible de déterminer pratiquement le pourcentage en masse que représente la phase argileuse. On peut alors se contenter d'un critère granulométrique en assimilant phase argileuse et fraction massique de diamètre de grain inférieur à 2µm.

Parallèlement à l'identification des argiles, il est également important de caractériser la structure du réseau de pores intergranulaires. En effet, c'est dans cet espace que s'opèrent les phénomènes de transfert hydrique et sa morphologie influe donc sur les valeurs des coefficients de transfert correspondants. Plusieurs techniques complémentaires peuvent être utilisées pour caractériser ce réseau poreux: voir Tableau II.

L'eau dans le matériau terre, notion de paramètres thermiques apparents

Comme nous l'avons dit en introduction, les matériaux auxquels nous nous intéressons ici contiennent toujours de l'eau. Celle-ci pourra être caractérisée par sa proportion en masse (w) ou en volume (θ) avec :

$$w = \frac{\text{Masse d'eau}}{\text{Masse totale}} \quad \text{ou} \quad \theta = \frac{\text{Volume d'eau}}{\text{Volume total}} \qquad (1)$$

$$\theta = w.d_s \quad (d_s : \text{densité sèche})$$

En fonctionnement normal, l'eau adsorbée par le matériau terre provient de la vapeur d'eau contenue dans l'air et elle est localisée essentiellement dans la phase argileuse qui possède une très grande surface spécifique et les pores les plus petits. Pour caractériser cette tendance à fixer l'eau ("hygroscopicité"), on réalise en laboratoire des "isothermes d'adsorption" : relation teneur en eau à l'équilibre en fonction de l'humidité relative de l'air (H.R.). La Figure 3 en présente des exemples qui montrent bien qu'en l'occurence ce n'est pas la densité sèche le paramètre important mais bien le type de terre. A l'équilibre à une teneur en eau donnée, on aura "condensation capillaire" (apparition d'eau liquide) dans les pores de rayons inférieurs à un seuil r(q) que l'on peut estimer, connaissant l'isotherme d'adsorption, par la relation de Laplace-Kelvin :

$$-\frac{2\,\sigma(T)}{r(\theta)} = \frac{\rho_l RT}{M} \operatorname{Log} H.R.(\theta) \qquad (1)$$

Avec :

σ : coefficient de tension superficielle air/eau (0,073 N/m à 20°C)
T : la température du milieu (°K).
ρ_1 : masse volumique de l'eau (998,3 kg/m³ à 20°C).
R : constante des gaz parfaits (8,3143 J/mole.°K)
M : masse molaire de l'eau (18,01534 10^{-3} kg/mole).

Sous l'effet d'un gradient thermique, notamment, le potentiel de l'eau dans le matériau terre peut être modifié de manière différentielle et divers mécanismes de transferts et/ou changement d'état apparaissent alors. Philip et De Vries ont, les premiers, formulé les équations générales traduisant ces transferts couplés de masse et de chaleur dans un milieu poreux humide [6]. Depuis, de très nombreux travaux ont porté sur ce thème (Voir par exemple : [7], [8] ou [9]). Nous nous contenterons, ici, de rappeler quelques résultats en relation avec la notion de paramètres thermiques apparents .

Si l'on suppose vérifiées un certain nombre d'hypothèses dont les plus importantes sont : milieu homogène, matrice solide indéformable et phase liquide incompressible, fluides parfaits (vapeur d'eau et air), pas d'hystérésis, pas d'effet de gravité, pas d'échanges radiatifs, équilibre thermique instantané, etc..., le premier principe de la thermodynamique (conservation de l'énergie) permet d'écrire l'équation de la chaleur, pour un milieu poreux humide, sous la forme :

$$C\frac{\partial T}{\partial t} + \rho_l L\frac{\partial \theta_v}{\partial t} - \rho_l W\frac{\partial \theta_l}{\partial t} = \mathrm{div}\left(\lambda\ \mathrm{grad}\ T\right) - \mathrm{div}\left(L q_v\right) - C_m q\ \mathrm{grad}\ T \quad (2)$$

Variation d'enthalpie (a) (b) (c)

Où (a) représente le transfert de chaleur purement conductif, (b) le terme de transport par chaleur latente et (c) celui par chaleur sensible avec :

t : le temps (s).
C : capacité calorifique ($J/m^{3\circ}K$).
L : enthalpie de vaporisation (2454,3 J/kg à 20°C).
W : "chaleur de mouillage" (J/kg).
λ : conductivité thermique (W/m°K).
θ_v , θ_l : teneurs en eau volumiques liquide et vapeur (m^3/m^3).
q_v, q : densités de flux de vapeur et de flux total ($Kg/s.m^2$).
C_m : capacité calorifique du mélange air + vapeur d'eau ($J/m^{3\circ}K$).

S'il n'existe dans le milieu que des forces motrices d'origine thermique, une analyse d'ordres de grandeur permet de négliger le terme (c) devant les deux autres. En développant le terme (b) l'équation (2) prend alors la forme suivante :

$$C\frac{\partial T}{\partial t} + \rho_l L\frac{\partial \theta_v}{\partial t} - \rho_l W\frac{\partial \theta_l}{\partial t} = \mathrm{div}\left[\left(\lambda + \rho_l L D_{tv}\right)\mathrm{grad}\ T\right] + \mathrm{div}\left[\left(\lambda + \rho_l L D_{\theta v}\right)\mathrm{grad}\ \theta\right] \quad (3)$$

Où D_{tv} est le coefficient de diffusion de la vapeur sous l'effet d'un gradient thermique et $D_{\theta v}$ le coefficient de diffusion de la vapeur sous l'effet d'un gradient de teneur en eau. Si, de plus, on retient l'hypothèse d'une humidité répartie de manière uniforme, (3) peut se ramener à une expression "classique" de la loi de Fourier :

$$C^*\frac{\partial T}{\partial t} = \mathrm{div}(\lambda^*\mathrm{grad}\ T)\ \text{avec}\ \lambda^* = \lambda + \rho_l L D_{tv}\ \text{et}\ C^* = C + \rho_l L\frac{\partial \theta_v}{\partial T} - \rho_l L W\frac{\partial \theta_l}{\partial T} \quad (4)$$

λ^* et C^* seront considérés comme étant les paramètres thermiques apparents du milieu poreux auxquels on a accès par la mesure.

Dispositif de mesure des paramètres thermiques

Pour mesurer la conductivité thermique et la capacité calorifique, nous utilisons des méthodes de mesure en régime transitoire imposé par "sondes à chocs thermiques".

Rappelons que le principe de ce type de méthode consiste à créer un choc thermique dans le matériau, dont on veut mesurer les propriétés thermiques, par l'intermédiaire d'un élément chauffant alimenté électriquement. Une réponse à cette excitation est mesurée en transitoire par l'intermédiaire d'un capteur placé dans le matériau ou dans l'élément chauffant. La connaissance de la forme analytique de la "fonction de transfert" entrée/sortie correspondant à une géométrie donnée permet d'identifier les paramètres thermiques à partir des courbes expérimentales [10].

Ces méthodes existent depuis plus d'un demi-siècle et sont largement utilisées dans différents domaines car elles présentent de nombreux avantages : simplicité de l'appareillage, rapidité de la mesure, automatisation possible et, surtout, possibilité d'opérer in-situ dans des conditions hygrothermiques quelconques en respectant l'état physique du milieu. Pour notre part, nous avons cherché à optimiser des sondes en fonction de l'usage que nous souhaitions en faire. En particulier, nous avons conçu une sonde "monotige", pour la mesure de la conductivité thermique, et une sonde "bitige" permettant également la détermination de la capacité calorifique [1, 10, 11]. Ces sondes (Voir Fig. 4) sont mises en place par perçage préalable. Les performances atteintes, grâce à un corps de chauffe breveté de très faible inertie thermique, nous ont permis d'atteindre une précision de l'ordre de ±5% quelle que soit la résistance thermique de contact sonde/matériau.

Mesures de l'évolution des paramètres thermiques du matériau terre en fonction de la teneur en eau et de la température

1. Méthodologie : Pour mener à bien cette étude, nous avons intégré nos sondes au sein d'un dispositif automatisé associant les fonctions de commande, d'acquisition et de traitement, pour la mesure des paramètres thermiques, au pilotage en température d'une étuve.

Pour des raisons d'ordre pratique, nous avons choisi d'étudier l'évolution des paramètres thermiques en fonction de la température à des teneurs en eau données. Nous avons donc réalisé successivement des teneurs en eau que nous avons choisies intermédiaires entre l'état sec et la teneur en eau à la fabrication : (w=0, 1, 2, 4 et 8%) ce qui couvre plus que la gamme des teneurs en eau qui peuvent être atteintes "naturellement" par le matériau terre en fonctionnement normal comme le montre la Figure 3. La gamme de température explorée allait de 0° à 60°C. Ces choix ont été motivés par le souci de se placer dans des conditions proches de celles du matériau réel en œuvre.

Pour obtenir ces teneurs en eau avec une répartition aussi homogène que possible, nous avons utilisé la méthode suivante : après injection dans les échantillons (cubes de 10 cm d'arête enveloppés dans des housses en matière plastique), de la masse d'eau liquide correspondant à la teneur en eau souhaitée, on opère une redistribution par vaporisation sous l'effet d'un chauffage micro-ondes. L'efficacité de cette méthode a été contrôlée en effectuant un certain nombre de mesures au banc gammamétrique de la répartition de l'eau dans le matériau. Les teneurs en eau finales étaient déterminées par pesée, par référence au poids sec, avec une précision de l'ordre de 0,1%.

2. Résultats : Dix échantillons de terre crue non-stabilisée réalisés à partir de sept terres différentes ont été sélectionnés. Pour ne pas alourdir notre présentation, nous ne reportons pas, ici, l'intégralité des résultats obtenus que l'on pourra retrouver dans [1]. Nous présentons, à titre d'exemples, les différents types de comportements observés en ce qui concerne l'évolution de la conductivité thermique (Voir Fig. 5) ou de la capacité calorifique (Voir Fig. 6). La Figure 7 effectue une synthèse, pour tous les échantillons de terres du Dauphiné, de la variation relative de conductivité thermique par rapport à l'état sec en fonction de la teneur en eau pondérale.

Terre	c (J/kg°K)
Morestel	891
Isle d'Abeau	815
CD300 N°2	813
CD300 N°1	818
Marchand	807
La Verpillière	820

Tab. IV : Chaleurs spécifiques à sec mesurées au calorimètre

3. Interprétation des résultats obtenus : Toutes les mesures réalisées en fonction de la teneur en eau ont montré que l'on pouvait admettre une variation linéaire de la capacité calorifique en fonction de la teneur en eau avec une pente égale à la capacité calorifique de l'eau (Voir exemple Fig. 6). On peut donc estimer la capacité calorifique d'un matériau terre humide à partir de la valeur obtenue à sec (Voir Tab. IV) par :

$$C_{humide} = C_{sec} + \theta . C_{eau} = 1000 . d_s . c_{sec} + 4{,}18\ 10^6\ d_s\ w \quad (5)$$

$$(J/m^{3} {}^{o}K) \qquad (J/kg^{o}K)$$

Si l'on considère maintenant l'évolution de la conductivité thermique en fonction de la teneur en eau pondérale (Voir exemple Fig. 5), on constate également une variation pratiquement linéaire aux faibles teneurs en eau. De plus, ce comportement est indépendant de la densité sèche du matériau considéré. On pourra donc estimer simplement la conductivité thermique d'un matériau terre humide, quelle que soit sa densité, par :

$$\lambda(w) = \lambda_{sec} (1 + K_{\lambda w} . w) \text{ pour } 0\% \leq w \leq 4\% \quad (6)$$

Où $K_{\lambda w}$ est une constante dépendant uniquement du type de terre. Nous avons relevé, pour les terres du Dauphiné, des valeurs de $K_{\lambda w}$ comprises entre 0,085 et 0,14 indépendantes de la densité sèche. Compte tenu de la diversité des comportements hydriques que l'on peut attribuer à des teneurs variables en argiles de nature différentes, un coefficient de + 20% par rapport à la valeur à sec, à défaut d'autres renseignements, donnera une estimation plausible de la conductivité thermique du matériau terre en œuvre dans une atmosphère d'humidité relative moyenne.

A sec et pour les teneurs en eau faibles, la conductivité thermique est toujours légèrement décroissante en fonction de la température. Ceci est dû à la variation de la conductivité thermique de la phase solide, en particulier du quartz. Aux teneurs en eau plus élevées, par contre, la conductivité thermique peut croître faiblement en fonction de la température. Il faut voir là l'influence de la phase fluide contenue dans l'espace poral (air + vapeur d'eau et, éventuellement, eau condensée), dont la conductivité thermique augmente en fonction de la température. Toutefois, ces variations restent faibles, ce qui montre que l'eau est fortement liée dans la phase argileuse d'un matériau terre, et, pratiquement, on pourra négliger l'influence de la température sur les propriétés thermiques utiles.

Conclusion

Le travail que nous venons de présenter peut être considéré comme le premier volet d'un programme plus ambitieux visant à la modélisation complète du comportement hygrothermique réel du matériau terre. Pour pouvoir résoudre les équations couplées de transfert de chaleur et de masse dans ce matériau, il faudra également disposer de valeurs des coefficients de transferts hydriques et de modèles de leur évolution en fonction du type de terre et des conditions de température et de teneur en eau. Ceci constitue actuellement un de nos axes de recherche.

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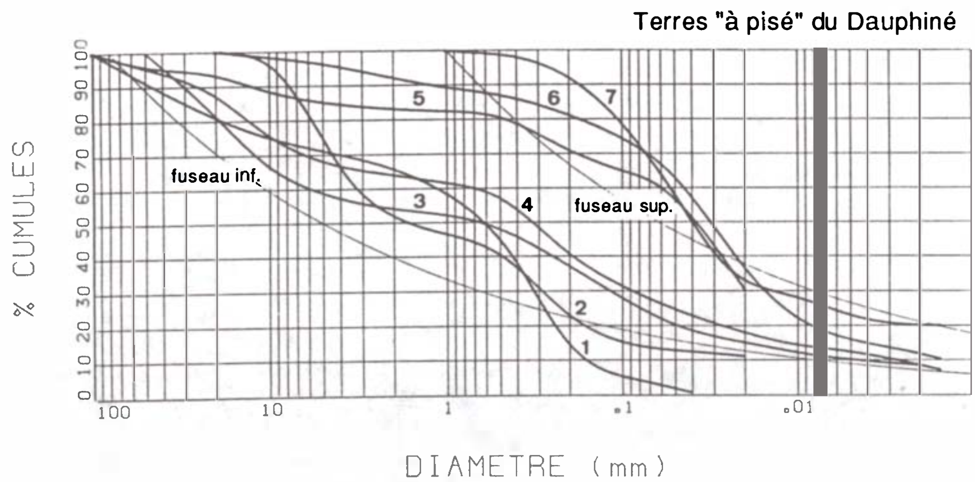

Fig. 1 : Courbes granulométriques de 7 terres "à pisé" du Dauphiné.

TERRE		PHASE SOLIDE GRANULAIRE							PHASE ARGILEUSE							
N°	Désignation	Quartz	Calcite	Feldpaths	Plagioclase	Hématite	Micas	% < 2 microns	Kaolinite	Illite	Illite/Mont.	Montmo.	Mont./Chlor.	Chlorite	Smectite	Vermiculite
1	Morestel	88	2	4	6	0	0	≈ 0	50	0	0	0	0	50	0	0
2	Marquis	100	0	0	0	0	0	6	tr	20	30	15	0	15	0	15
3	Isle d'Abeau	61	26	13	0	0	0	9	25	50	0	25	0	0	0	0
4	CD300 n°2	64	19	5	5	0	7	9	0	100	0	0	0	0	tr	0
5	CD300 n°1	88	2	5	5	0	tr	15	0	57	0	0	0	0	43	0
6	Marchand	80	0	0	20	0	0	13	10	40	20	0	20	10	0	tr
7	Verpillière	49	0	51	0	0	0	20	20	40	0	0	0	0	40	0

Tab.I : Caractéristiques des terres du Dauphiné étudiées.

	CARACTERISTIQUE	DEFINITION	OBTENTION	REMARQUE
GLOBALES	Porosité totale	$n = \frac{\text{Volume des pores}}{\text{Volume total}} = 1 - \frac{d_s}{d_g}$	pycnométrie porosimétrie mercure	eau, hélium... limitée au + petit pore accessible
	Densité sèche	$d_s = \frac{\text{Masse sèche}}{1000.\text{Volume total}}$	pycnométrie pesée	- état sec de référence
	Densité de grain	$d_g = \frac{\text{Masse sèche}}{1000.\text{Volume solide}}$	pycnométrie	généralement : 2,65
MATRICE SOLIDE	Distribution de diamètres de grain	Fraction massique de grains de diamètre d<do en fonction de do	tamisage + sédimentométrie	grains supposés sphériques
	Composition minéralogique	% relatifs et nature des minéraux	analyse X	diagramme de poudre microscopie électronique
	Composition chimique	% relatifs et nature chimique des minéraux	analyse X	généralement exprimée en oxydes élémentaires
RESEAU POREUX	Distribution de diamètres de pores	Fraction volumique de pores de diamètre d<do en fonction de do	porosimétrie mercure adsorption moléculaire analyse d'image	pores cylindriques par calcul (BJH) -
	Surface spécifique	Surface développée des pores ramenée à l'unité de masse	porosimétrie mercure adsorption moléculaire analyse d'image	par calcul direct (BET) -
	Géométrie du réseau poreux	Morphologie du réseau contiguïté entre phases coordinence des grains	analyse d'image	performances liées aux algorithmes d'analyse utilisés

Tab.II : Principales méthodes de caractérisation d'un milieu poreux granulaire.

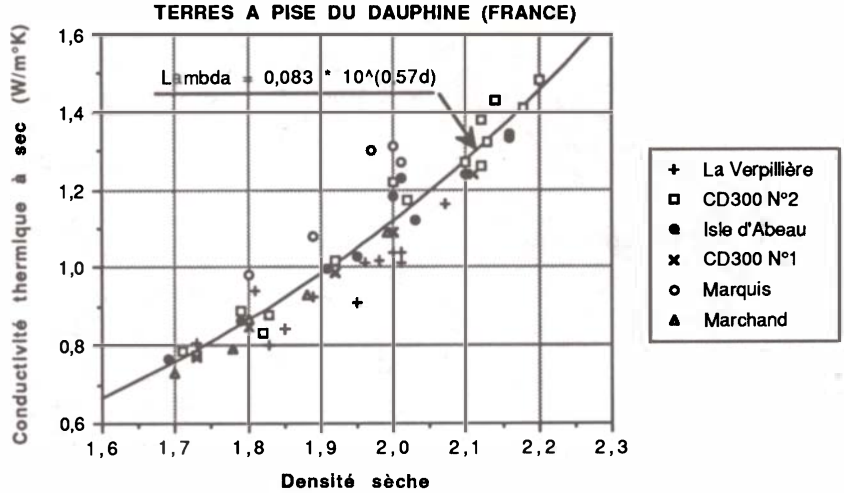

Fig. 2 : Influence de la densité sèche sur la conductivité thermique "à sec" [1, 2].

Distance interfoliaire	FAMILLE	FORMULE CHIMIQUE
7 Å	Kaolinite	$Si_2O_5Al_2(OH)_4$
10 Å	Montmorillonite	$Si_4O_{10}(Al_{2-x}Radical_x^{2+})(OH)_2Cation_x\,nH_2O$
	Illite (Micas)	$(Si_{4-x}Al_x)O_{10}(Al_2)(OH)_2K_x$
	Vermiculite	$(Si_{4-x}Al_x)O_{10}(R^{2+}_{3-y}R^{3+}_y)(OH)_2CE_{x-y}$
≈ 14 Å	Chlorite	$(Si_{4-x}Al_x)O_{10}(R^{2+}_3)(OH)_2(R^{3+}_xR^{2+}_{3-x})(OH)_6$

Tab III. : Les différentes familles d'argiles rencontrées dans le matériau terre [5].

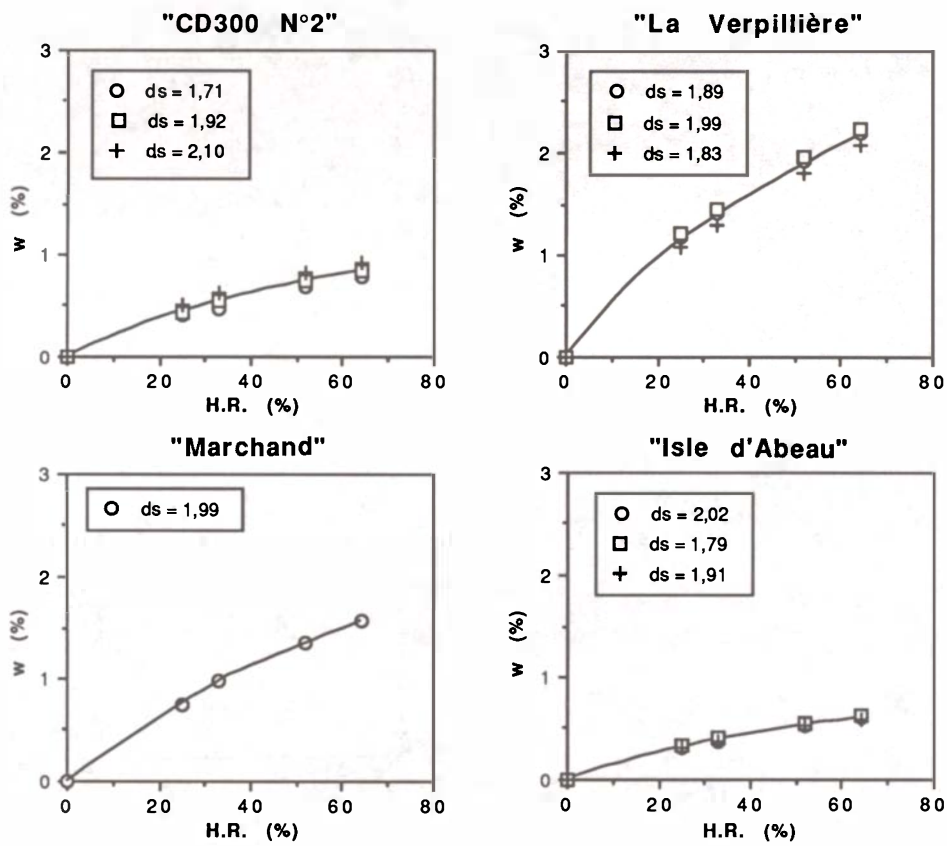

Fig. 3 : Isothermes d'adsorption pour 4 terres "à pisé" du Dauphiné.

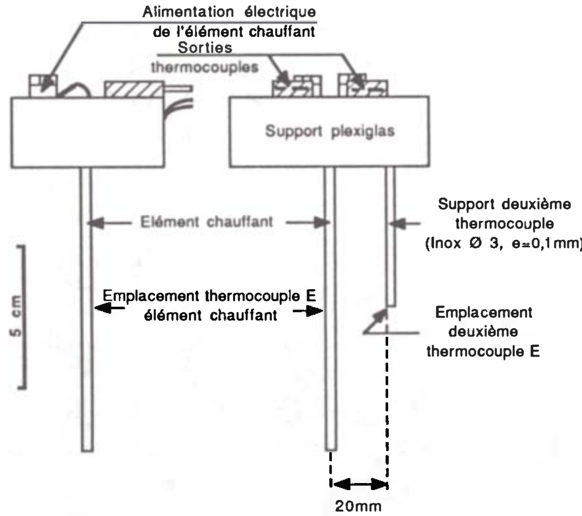

Fig. 4 :
Sondes utilisées pour la mesure des paramètres thermiques

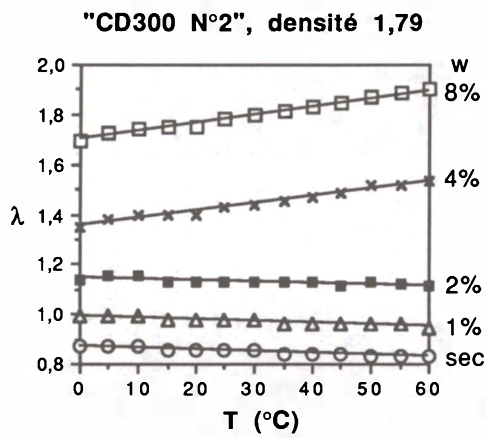

Fig. 5 : λ = f (T,w)

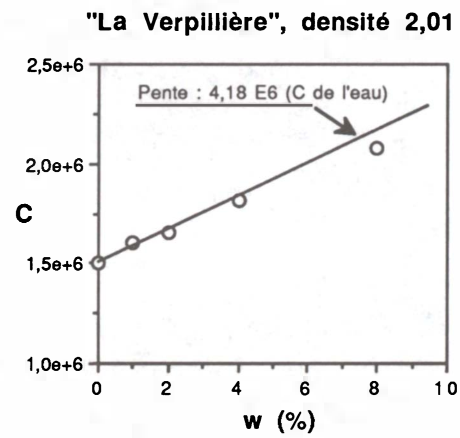

Fig. 6 : C = f (w) à 20°C

Fig. 5 & 6 : Exemples d'évolutions mesurées des paramètres thermiques en fonction de la température et de la teneur en eau

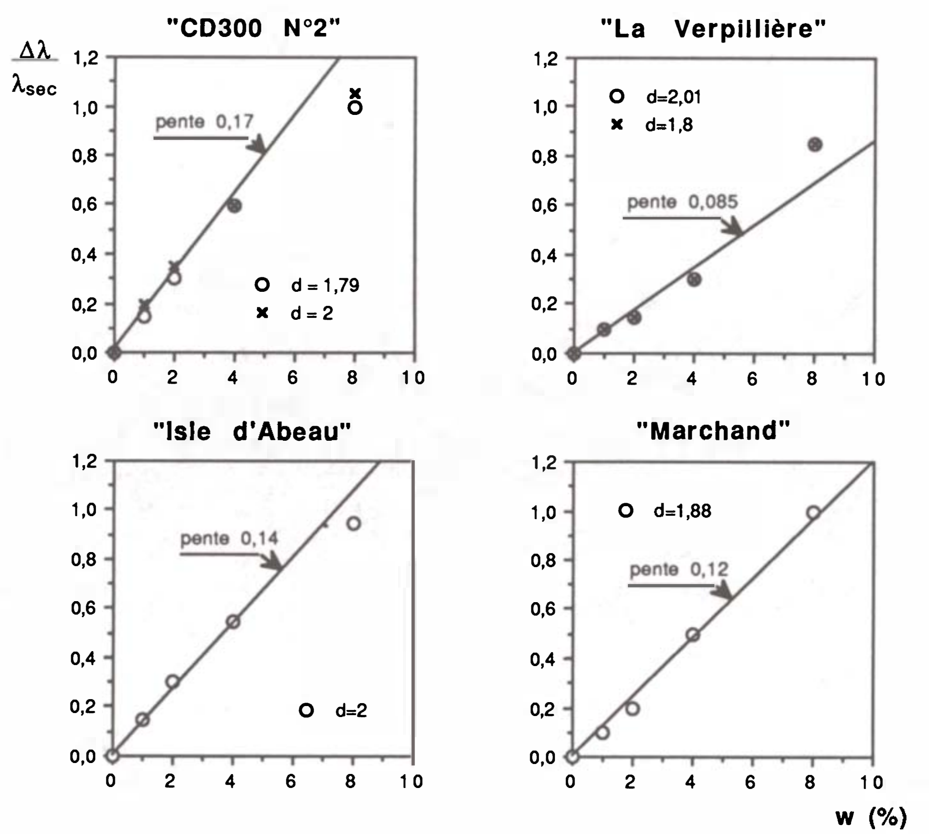

Fig. 7 : Variation relative de la conductivité thermique en fonction de la teneur en eau. Synthèse des résultats obtenus pour 4 types de terres "à pisé" du Dauphiné

ABSTRACT

Site Tulor 1 has become one of the most outstanding archaeological discoveries in recent years in the north of Chile being the oldest example of earth technology used for building a village in this country.
Efforts to preserve this site's ruins have generated joint research work which will combine the following studies:
Assessment of its present condition.
Identification of degrading agents threatening its extinction.
The construction of an experimental polygon.
Characterization of earth based materials.
Experiments will be oarried out using various techniques aimed at stabilizing the earthen village's wall.
At present, research work being conducted on these earthen head walls involves among other techniques the use of chemical surface treatments (consolidants), ethyl silicate based.

KEYWORDS

Conservation, Consolidation, Experimental Polygon

CONSERVACION DE UN SITIO ARQUEOLOGICO CONSTRUIDO EN TIERRA

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I. Sitio Arqueológico Tulor 1

El Sitio Arqueológico Tulor 1, denominado también Aldea de Tulor, está ubicado en el Salar de Atacama, a unos 10 kms. en dirección S.O. del Pueblo San Pedro de Atacama, Región de Antofagasta, Norte de Chile.

Según las investigaciones arqueológicas que se han efectuado, la cronología del Sitio se extiende desde los 400 años A.C. hasta los 100 años D.C., y correspondería al período intermedio temprano en la secuencia cultural de las regiones atacameñas. Se trataría de uno de los asentamientos permanentes de los inicios del período agropecuario de esta compleja cultura local con actividades de caza, recolección e incipiente agricultura (A. Llagostera et al., 1984; A.M. Barón, 1986)

La Aldea de Tulor consiste en 23 estructuras de planta circular, de las que se generan pasadizos y construcciones anexas de formas mixtas hasta un total de 106 estructuras dispuestas en compleja trama de crecimiento celular. Se accede a los recintos por vanos de puerta de dos tipos: los originales con dintel y los horadados en las paredes de tierra en distintas épocas, evidenciando una gran dinámica en su ocupación.

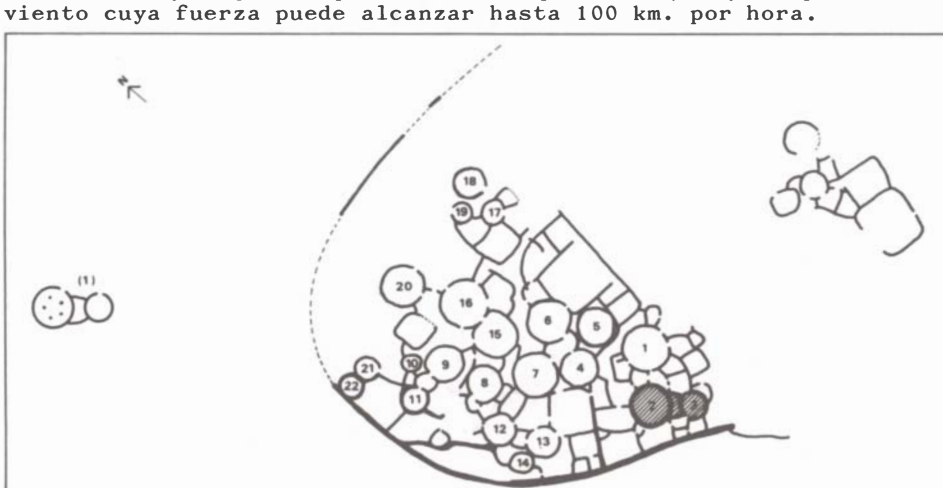
El conjunto está defendido por un muro de mayor volumen que el de las estructuras, dispuesto en semicírculo en dirección de sur a noroeste.

La construcción fue realizada con bloques de tierra modelados in situ, diferenciándose hiladas superpuestas. De los restos, que aún se conservan, se elevan muros hasta una altura de 1,85 m. La superficie total del Sitio que se conoce en la actualidad alcanza a 2.800 m^2

Aunque este Sitio ya era conocido desde la década de 1950 (G. Le Paige, 1957-58), la comunidad científica chilena puso en relieve su gran importancia sólo después que fuera redescubierto en el año 1981. Los trabajos arqueológicos se iniciaron en el año 1982 (Ver graf. 1, foto 1)

II. Problemas de Conservación

Este yacimiento se ubica en un medio ambiente deteriorado por el avance de la desertificación, la que, a su vez, ha sido causada por los cambios fluviales ocurridos en los últimos siglos en esa zona. La región del Salar de Atacama corresponde a un desierto de altura (2500 m. sobre el nivel del mar). El clima está influido por las condiciones que rigen en Los Andes Meridionales, con un comportamiento pluvioso cíclico en los meses de diciembre, enero y febrero. Los meses de invierno se caracterizan por la ausencia de lluvias y bajas temperaturas. En primavera, hay temporales de viento cuya fuerza puede alcanzar hasta 100 km. por hora.



Graf. N° 1 Sitio Tulor 1 Planta de Conjunto Escala: 0 10 m

(1) Polígono de Ensayos
▨ Estructuras en cuya forma se basó la reconstrucción

El medio ambiente es el mayor agente de degradación del Sitio de Tulor. En sus comienzos la desertificación sepultó la Aldea con arena arrastrada por el viento. La formación y avance de dunas han hecho evolucionar el deterioro de los restos de las construcciones de acuerdo a sus propios cambios. El material que desplaza el viento es arena con gran cantidad de sales solubles, las que se depositan principalmente en las cabezas de muro. Las precipitaciones disuelven las sales. Luego los muros absorben la solución que contamina el material de tierra provocando efectos degenerativos irreversibles, tales como cristalización, subflorescencia y exfoliación. Este estado favorece ampliamente el efecto abrasivo del viento y arena sobre las cabezas de muro afectadas. A lo anterior se suma una enorme gradiente de temperatura entre el día y la noche, y una humedad relativa baja, factores que propician la formación de grietas y fracturas, así como la meteorización del material, los cuales, a su vez, actúan como agentes multiplicadores del deterioro.

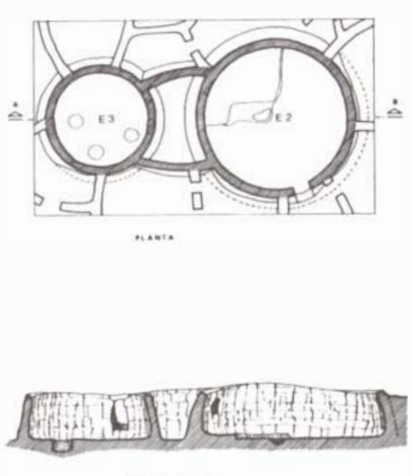
Las excavaciones arqueológicas, practicadas en temporadas sucesivas entre los años 1982 y 1985 (10% de la superficie descubierta del Sitio), expusieron al intemperismo estructuras que durante siglos estuvieron cubiertas por la arena, lo que, indudablemente, ha provocado un incremento de su degradación en los últimos años.

Otro factor importante de destrucción lo constituye la actividad turística que, desde hace algunos años, se ha intensificado en la zona.

III. Criterios de Intervención

Las investigaciones han determinado que debido a los elementos climáticos adversos, en la actualidad resulta improbable crear las condiciones de conservación del Sitio excavado para ser exhibido. No obstante, la preocupación va más lejos al tener que enfrentar el hecho de que las estructuras que no han sido excavadas y que se encuentran enterradas en forma natural también sufren el efecto del desgaste progresivo de las cabezas de muro, ya que la arena que las cubre no es suficiente barrera para que los vientos abrasivos cumplan su efecto devastador. Prueba de lo anterior es la diferencia de altura de muros entre estructuras localizadas en el sector norte y sur, 0,20 y 1,85 m. respectivamente. Considerando lo anterior se preve próxima la extinción del Sitio en su estado actual.

La importancia de este yacimiento para la investigación arqueológica y de otras disciplinas científicas exige agotar los esfuerzos para su conservación. De este modo, los criterios de intervención se han hecho sobre la alternativa de conservar el Sitio bajo tierra, conscientes además de otras experiencias que recomiendan esta alternativa como la más óptima en sitios con problemas insolubles para la tecnología actual (A. Alva et al., 1984; N. Stanley, 1984)



Graf. Nº 2 Plano de las estructuras Nºs 2 y 3 utilizadas como modelo en la reconstrucción ideal usada como polígono de ensayos.

Escala: 0 2 m

IV. Conservación del Sitio

IV.1. Polígono de Ensayo: Reconstrucción ideal de estructuras típicas

La necesidad de comenzar las investigaciones para la conservación del Sitio motivó la construcción de una estación experimental de campo que, a su vez, se pudiese utilizar como Polígono de Ensayos. Además, de acuerdo con las investigaciones arqueológicas, se podrían reconstruir hipotéticamente las condiciones ideales de funcionalidad de las estructuras circulares agregando el elemento techumbre (inexistente) y el acceso a nivel del suelo a diferencia de la posición semienterradas en que se encuentran en la actualidad.

Se escogió la forma de las estructuras (E) circulares típicas Nº 2 y 3 (Ver graf. 1 y 2) que son las mejor conservadas del conjunto, para hacer las réplicas. La reconstrucción incluiría, además, el espacio que se interpone entre ambos círculos unidos por muros de enlace semicirculares.

A poco más de 30 m. desde las últimas construcciones de la Aldea, en dirección oeste, se allanó un espacio de 300 m^2 para construir las réplicas y se replantearon las dos circunferencias. La base se estabilizó picando la capa de tierra que luego se humedeció y apisonó lográndose una base de fundación compacta.

El Sitio de Tulor, está construido sobre un depósito aluvial de tierra arcillosa, el material empleado en la construcción de la Aldea procede del mismo lugar. De igual modo para el Polígono de Ensayo, se escogió el material de un sector inmediato al terreno a construir. Debido a la baja granulometría y excesiva plasticidad del material de tierra fue necesario hacer una mezcla agregando un 30% de arena.

Para aproximarse a la técnica de bloques modelados in situ de los muros originales, se optó por la técnica de tapialera con un molde sobredimensionado de 0,40 x 0,45 x 0,60, dando lugar al desbaste posterior a fin de dar la apariencia de los muros originales. Fue necesario superar algunas dificultades para esta técnica de tapial con material de baja granulometría. Esto obligó a hidratar la mezcla sobre los niveles requeridos, lo que se manifestó en el agrietamiento de los bloques durante el proceso de secado. Este inconveniente se superó ajustando la cantidad de agua en la mezcla y con la colocación de cobertizos de hule para impedir la rápida evaporación en este ambiente de sequedad extrema. Al concluir la albañilería a la altura de 1,75 en la E2 y 1,60 en la E3, se desbastaron los muros dejando una leve inclinación hacia el interior. Además, se cortó un vano de ventana que se comunica con el espacio intermedio. En la E3 se cortó en el muro un vano de puerta, imitando este rasgo original de la dinámica de ocupación.

La reconstrucción hipotética de la techumbre se hizo en base a evidencias arqueológicas que mostraron indicadores débiles de una armadura de techumbre en posición radial. Esto fue rápidamente aceptado, ya que resulta la solución más lógica a la forma circular de las estructuras y permite su construcción de forma cónica aprovechando la menor longitud de las vigas. El uso de pies derechos en el interior se pudo advertir por huellas dejadas en la E16 que es la de mayor diámetro del conjunto (7 m.)

Se hicieron las armaduras de techumbre radiadas y en forma cónica con maderos de chañar (gourliaea cortican). En la E2 se colocaron cinco pies derechos a media luz de las vigas radiales para aminorar la flexión. En la E3 no fue necesario el uso de pies derechos por su menor tamaño. Las vigas se unieron con varillas costaneras de 2,5 a 5 cm. de diámetro formando círculos concéntricos. Todas las piezas de madera se amarraron con cuero de camélido, según la técnica vernacular andina.

Las cubiertas se hicieron con una capa de 0,10 m. de ramas de la especie arbustiva brea (atriplex), colectadas en los alrededores del Sitio. El relleno se hizo con ramas verdes y secas que fueron colocadas en paquetes en posición radial. Sobre las ramas se colocó una capa de barro de 0,05 m. de espesor, cuya dosis fue de un 70% de arcilla, un 30% de arena y un tercio de volumen con paja de trigo. Finalmente se colocó una cubierta de terminación que consistió en una mezcla de un 25% de arcilla más un 75% de arena. Esta última capa sellante de grietas y fisuras deberá ser mantenida constantemente (E. Muñoz., 1987, describe en detalle la construcción de la estación de campo y polígono de ensayo)

En uso como Estación de campo, las casas reconstruidas ofrecen una excelente adaptación al clima del desierto, tanto por la inercia térmica de sus materiales, el espesor de sus muros, el tipo de techumbre y quizá, también, por su forma circular. En el ambiente de Tulor de grandes oscilaciones de temperatura, las estructuras se mantienen frescas de día y cálidas de noche.

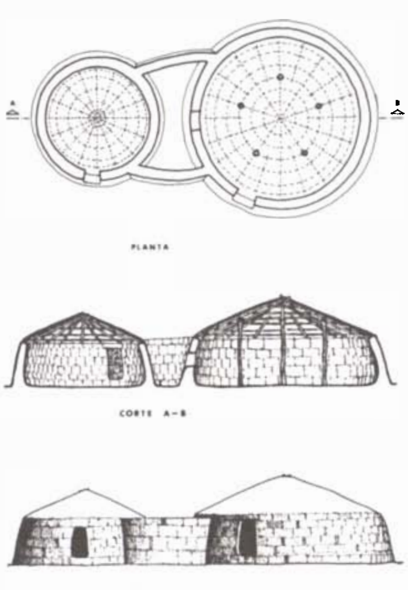
El uso como Polígono de Ensayo se ha diversificado entre mediciones térmicas, mediciones del desgaste de los muros expuestos a los vientos abrasivos y al intemperismo en general. También se han ensayado soluciones "capping" (1) previamente a su aplicación en los muros originales. De mayor interés han sido los tratamientos superficiales y pruebas con sustancias químicas a base de silicato de etilo (2), gracias a lo cual podrían ser aplicadas sin riesgo en los muros originales (Ver graf. 3, foto 4)

IV.2. Investigación: caracterización de materiales y ensayos específicos

Las investigaciones preliminares consistieron en la caracterización físico-química del material de tierra usado en la construcción de las estructuras. Este material de procedencia aluvial se compone de un mayor porcentaje de arcilla, limo y arenas finas, por lo que su granulometría es baja y su plasticidad exagerada. La manifestación física es un alto índice de retracción y consiguiente agrietamiento durante el proceso de fraguado. Los análisis determinaron altas concentraciones de sales solubles, que varían en los distintos lugares del yacimiento y también en los muros de las estructuras. Otras investigaciones se han orientado a la estabilización de las cabezas de muro, las que, como se ha mencionado, sufren un constante proceso deteriorante.

(1) Morales G., Ricardo (1983) define la técnica "capping" para la estabilización y recomposición de las cabezas de muro expuestas al intemperismo.

(2) Chiari, Giacomo (1983); Schwartzbaum M., Paul et al. (1983) y Morales G., Ricardo (1983) comunicaron interesantes experiencias sobre el uso de consolidantes en base a silicato de etilo.



Graf. N° 3 Plano del polígono de ensayos y estación de campo.

Escala: 0 2 m

IV.2.1. Estratigrafía de muros

Los trabajos de investigación y sondeo permitieron comprobar la existencia de una estratigrafía claramente definida, con distintas propiedades mecánicas dentro de un mismo muro, situación que se encuentra directamente relacionada con los mecanismos de deterioro que éste sufre.

Para el estudio de dicha estratigrafía se hizo un pequeño corte en el muro norte de la estructura N° 57 y se extrajeron las siguientes muestras:

Tabla I. Estratigrafía del muro:

Muestra	Ubicación	Espesor	Características
1	superficial	2-4 cm.	costra dura
2	2° estrato	2-4 cm.	polvo muy fino, sin cohesión
3	3° estrato	6-10 cm.	muy duro y compacto
4	muro no alterado	no determ.	material homogéneo

Tabla II. Análisis de muestras por espectrometría de rayos X: Este análisis permite identificar cuantitativamente los componentes más importantes de la muestra.

Muestra	Elementos analizados % en peso										
	Fe_2O_3	TiO_2	CaO	K_2O	SiO_2	Al_2O_3	MgO	Na_2O	SO_3	Cl	$NaNO_3$
1	3,8	0,5	3,3	1,9	39	9,1	1,5	15	0,4	10,6	0,14
2	3,8	0,4	4,6	2,0	41	9,6	2,0	13,5	0,2	10,0	0,19
3	3,3	0,4	3,2	1,6	34,5	7,5	1,4	17,6	0,5	13,6	0,12
4	4,5	0,6	4,1	2,8	59,4	14,8	2,4	4,4	0,5	2,0	0,005

Tabla III. Determinación granulométrica (% en peso que pasa por las mallas, Norma ASTM) pH de muestras.

Tamiz N°	Muestra 1	Muestra 2	Muestra 3	Muestra 4
4	100	100	100	100
10	98	99	100	100
20	96	98	99	98
40	94	96	97	92
60	92	94	94	86
200	67	64	69	51
pH	6,5	6,7	6,6	6,3

Foto N° 1: Detalle de estructuras excavadas en pleno proceso de deterioro.

Foto N° 2: Estructuras sin excavar casi extinguidas por los agentes degradantes.

IV.2.2. Caracterización del material de arrastre

Se realizó una serie de análisis que permitieran, mediante una aproximación volumétrica, conocer la fuerza del impacto del material de superficie causado por el viento sobre los muros de la Aldea.

Tabla IV. Determinación de granulometría del material superficial de arrastre.

Tamiz :	4	10	20	40	60	200
% peso que pasa	100	68	35	32	28	8

Tabla V. Constantes físicas del material superficial de arrastre.

Densidad (Kg/m3)	Material retenido en malla # 10	Material bajo malla # 10
- Real saturada	2.509,0	2.606,0
- Real seca	2.406,0	2.593,0
- Neta	2.608,0	2.737,0
Absorción %	2.51	2.04

- Coeficiente volumétrico medio C = 0,30 (partículas retenidas en malla # 10)

IV.2.3. Soluciones capping experimentales

Se experimentaron soluciones capping con materiales tradicionales como tierra-arena-cemento y cal. Los mejores resultados se consiguieron con una mezcla de la siguiente dosis: tierra 20,0% + arena 75,0% + cemento 2,5% + cal 2,5% = 100,0 % más un tercio del volumen en fibra vegetal.

Este capping se degradó casi totalmente 26 meses después de su colocación debido al desgaste del viento abrasivo. Sin embargo, tiene la ventaja de un desgaste parejo y no se produjo horadación eólica bajo la capa, efecto colateral muy frecuente cuando se aplica esta técnica debido a la diferencia de dureza con los materiales de la cabeza de muro y la mezcla capping. Esta mezcla se probó

Materiales

1. Cemento Portland
2. Cal hidráulica
3. - Agente consolidante OH (Wacker Strengthener OH)
   - Hidrorrepelente 090L y 090S (Silicona Wacker 090L y 090S) Wacker Chemie:GMBH Werk Burghausen 8263. Burgnausen/OBB West Germany. Teléfono (08677) 832222, Télex 56944.

en altura de 1,75 m. (en el Polígono de Ensayo) con resultados óptimos comprobados 4 años después de su colocación.

IV.2.4. Ensayo de consolidación e hidrorrepelencia en muros del polígono de ensayos

De acuerdo a los objetivos para cuales fue creado el polígono de ensayo, se han realizado sobre sus muros numerosas pruebas de tratamiento superficial con productos a base de silicato de etilo fundamentalmente. Dichas pruebas, cuya finalidad ha sido la de verificar el adecuado comportamiento de los productos en el clima desértico del norte de Chile, ha permitido a la vez, optimizar el método de aplicación y determinar, previo estudio de las condiciones ambientales, las horas del día adecuadas para realizarlo.

Como un primer acercamiento al problema, el uso del polígono de ensayo ha sido altamente provechoso, pudiendo comprobarse en primera instancia que la protección de las zonas tratadas en los muros ha sido efectiva contra los agentes deteriorantes.

IV.2.5. Ensayos de consolidación e hidrorrepelencia de soluciones capping con técnica de apisonado

En vista de los resultados obtenidos en el polígono de ensayo, se profundizó en la investigación, aplicando el tratamiento superficial a muestras realizadas con técnica de apisonado (solución capping en proceso de investigación) Para tal efecto se fabricaron 30 cubos de tierra de Tulor de 64 cm3 (4 x 4 x 4)
10 cubos : muestras testigo
10 cubos : consolidante (Wacker Strengthener OH)
10 cubos : consolidante + hidrorrepelente (Wacker S. OH + Silicona Wacker 090L)

Estos ensayos, actualmente en desarrollo, tienen como objetivo comparar el comportamiento del material al ser sometido a procesos de erosión y comprensión, así como impregnación con niebla salina.

De los resultados que se obtengan de estos ensayos dependerá la aplicación de los productos mencionados a la solución capping definitiva.

V. Conclusiones

El Sitio Tulor 1 proyecta su importancia a diversas áreas de interés científico. Además de contribuir con importantes indicadores para la arqueología como asentamiento sedentario temprano; para la historia de las tecnologías representa el Sitio conocido más antiguo construido de tierra hasta ahora en Chile.

Las investigaciones realizadas sobre las condiciones y problemas de conservación que afectan al yacimiento, conllevan a presumir que es poco probable crear las condiciones necesarias para que permanezca como sitio excavado para ser exhibido. No obstante, la degradación de las estructuras, aun estando enterradas, hace necesaria la investigación de técnicas específicas para estabilizar las cabezas de muro en constante deterioro por los agentes mencionados. Estas soluciones se deberán complementar con la colocación de barreras de control eólico y la elaboración de un plan permanente de preservación del Sitio post intervención.

Los avances que se han logrado hasta ahora y que aún se investigan se relacionan con la técnica para la estabilización de las cabezas de muro mediante el reemplazo del material de tierra, contaminado y degradado irreversiblemente, por una mezcla de arcilla y arena de granulometría controlada. Esta es aplicada en los muros mediante el apisonado, lográndose una efectiva integración entre el material del muro y el de reemplazo. Las cabezas de muro estabilizadas serían sometidas a tratamiento a base de silicato de etilo, en caso de obtener buenos resultados con este producto.

Por tratarse de un proyecto actualmente en desarrollo, los resultados se encuentran en proceso de elaboración, por lo cual, serán dados a conocer posteriormente.

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Foto N° 3: Vista aérea del Sitio Tulor 1, en donde se aprecian las estructuras excavadas entre los años 1982-85. Foto: Ana M. Barón.

Foto N° 4 : Polígono de Ensayos construido a semejanza de las estructuras originales N°s 2 y 3.

Fotografía y fotomecánica
Ottorino Ovalle O.

AN INVESTIGATION INTO THE PATTERN OF DETERIORATION OF *DAGA* (EARTH) STRUCTURES AT ZIMBABWE TYPE MONUMENTS

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ABSTRACT

The majority of prehistoric structures in southern Africa were constructed of *daga*, a local clayey soil which is still being used for building houses in the rural areas. Although the material does not normally survive for long periods, at some archaeological sites the structures remain as evidence of the Iron Age communities. If these ruined structures are to be presented to the public as site museums, there is a need to preserve them. In southern Africa, conservation of archaeological sites has placed emphasis on dry stone walls and neglected the *daga* structures. The goal of the current research programme is to redress this situation. The project seeks to understand the material and the causes of deterioration of the prehistoric structures by documenting the symptoms of distress and nature of decay associstion with them. This approach is already yielding results which are helping to understand the behaviour of the material and structures built of *daga*.

KEYWORDS

Conservation, Prehistoric structures, Excavated structures, Patterns of decay, Wattle and daub, Southern African vernacular architecture, Physical and chemical composition of *daga*.

INTRODUCTION

The Zimbabwe-type monuments scattered all over Southern Africa are well-known by both academic researchers and tourists for their prehistoric dry stone wall structures. The ruined monuments, whose settlement patterns reflect the socioeconomic arrangement and cultural ethos of the African Iron Age communities, are dated AD 1100 - 1500. More than 150 of these dry stone or Zimbabwe-type monuments have been recorded in southern Africa. The most famous and largest of these Iron Age monuments are the Great Zimbabwe ruins, which comprise the dry stone walls and numerous *daga* (earth) structures of varying sizes, constructed over an area of approximately 720 hectares. This ancient settlement, which provided most of the data in this paper, is located 29 km south-east of Masvingo, a modern town in south-central Zimbabwe.

The dry stone walls to which the academic researcher and the visitors have been attracted can only be described as the skeleton of the prehistoric monuments. The flesh is the dwelling structures, built with Africa's most common indigenous building material, *daga*, a puddled clayey soil, binding together naturally weathered granite gravel aggregate. When dry, the mixture forms a durable material, which is described as "*daga* cement" or "granite cement" because of its characteristics. In prehistoric times, the builders utilized the plastic properties of the material which was wet, to construct substantial round houses and moulded fittings on the walls and floors. The fittings were mainly benches, kerbs and basins. At times, decorative motifs were placed on the walls or floors [1]. Some of the *daga* features are less easily identifiable today. Different *daga* surface textures and colour changes were achieved by exploiting the varied clay mineral deposits which were derived from the local parent geology. The most carefully selected and worked *daga* produced a hard, smooth surface which was able to survive considerable wear and exposure. The material was also used for constructing smelting furnaces and grain bins. Some of the *daga* structures have partially survived in various forms for 500-600 years. In prehistoric times, the domestic *daga* structures were enclosed by the dry stone walls, in order to divide space into areas and form courtyards and enclosures. In some sections of the settlement, the stone walls were also plastered with *daga* so that the enclosure presented a homogenous appearance with the dwellings.

BACKGROUND TO INVESTIGATIONS

Although some attempts have been made over the past decade to conserve the structures at Zimbabwe-type monuments, most conservation efforts have focused on the dry stone walls to the exclusion of the *daga* features [2,3]. However, it should be recognised that the *daga* structures are part of the monuments, and it is difficult to visualise the sites in their proper historical perspective without them. Overemphasis on the dry stone walls gives visitors and researchers a slightly distorted interpretation of the Zimbabwe-type monuments.

Unlike the dry stone walls, very few *daga* structures remain above ground. Most of the structures are concealed by vegetation, soil and rubble deposits. Of those above ground, only partial structures survive as evidence of the proto-historic features. The evidence of the underground structures are the numerous mounds scattered inside and outside the dry stone enclosures. The mounds are the results of the deterioration of the once complete *daga* structures. Archaeological excavation of these reveal the remains of the prehistoric *daga* features. In some cases, these will be floor fittings, dividing walls and, at times, artistically moulded and decorative features of houses expressing something of the symbolic and figurative ethos of the proto-historic communities. If these structures are to be made the subject of presentation or research work, there is a need to retard the process of disintegration and deterioration. This is even more critical for the ruined structures above ground. If left to the ravages of nature, they will become meaningless mounds of soil dotted in and around the dry stone monuments.

At the Great Zimbabwe ruins some attempts were made two decades ago to preserve the *daga* structures using chemical water-repellents. These preliminary attempts failed, partly due to inadequate understanding of the deterioration mechanisms, and to the high costs of the treatment. The primary aim of the project reported in this paper is to document and quantify the nature of decay associated with *daga* structures. It is hoped that this will give an insight into the failure mechanism and provide practical guidelines for the conservation of prehistoric remains.

FIELD STUDY

Generally, physical weathering, atmospheric conditions, movement of soluable salts and biodeterioration account for most of the decay associated with *daga* structures. However, the rate of deterioration is a function of the *daga* composition, texture, construction methods and subsequent use of the structures. Prehistoric *daga* structures represent an end-product of the sequence of events ranging from construction and occupation to abandonment and transformation to a partially eroding archaeological feature. In the case of excavated structures, a new process of transformation and decay will begin again as soon as they are exposed to the "new environment" above ground. In order to understand the pattern of decay it was necessary to begin investigations by analysing the designs and methods of construction employed by communities still using the material.

Investigations on contemporary daga constructions

In southern Africa *daga* houses are still being constructed, albeit with some modification of the proto-historic methods. However, study of the contemporary construction methods can give insight into the failure mechanisms associated with such structures and an indication of the nature of structural problems encountered when using *daga* as the primary building material. Such study provides an overview of the inherent weakness in the construction methods and also indicates likely patterns of use-wear before abandonment. However, there is a weakness in using such a method of analysis: that of assuming that no changes in construction and use-wear occurred from prehistoric times to the present. Today we know that a large percentage of *daga* structures are on a temporary basis until the owner can afford to build in brick. Thus, the temporary nature affects the design and construction procedures.

Contemporary *daga* house construction begins by building a timber framework which is then packed and plastered with *daga* both internally and externally. The building method is similar to wattle and daub construction. Only the floors and internal fittings are made exclusively of *daga* material. The surface finish and hence the *daga* mixture used on the floor is different from that used on the walls. The floor material contains a higher ratio of clay to gravel. This gives the material greater plasticity for moulding such fittings as the fireplace, the bench and wall shelves. At times, cow dung is added to the material to act as a binder and for colour variations. For the walls, the gravel ratio is increased to give the surface a rougher but strong finish. During occupation the house is regularly plastered using a weaker *daga* mixture at least once every two to three years. However, the floor receives a more regular maintenance by having a cow dung coating at least once every three months. This gives a hard protection to the surface. During occupation, the rest of the structure receives adequate protection from the elements through proper maintenance of the thatched roof. Most people prefer building on bed rock in order to avoid waterlogging and termite attack.

Besides the expected shrinkage fractures, cracks appear on the structure just after construction. These tend to follow the joints between the floor, fittings and wall. These cracks are normally covered up during routine maintenance by plastering. Despite regular maintenance, two areas of floor usually show signs of distress due to use wear. These are:

(a) The fireplace, which generally exhibits multiple micro-fractures superimposed on large deep radial cracks (Fig. 1a). This is largely due to the continuous heating and use of this area. Apart from cooking, this space is the most utilized area in the house.

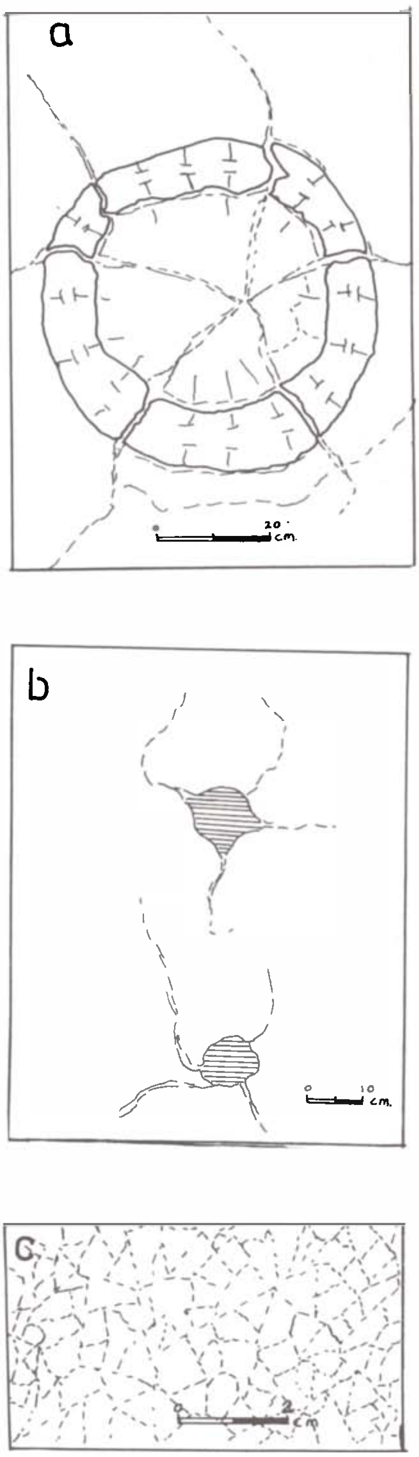
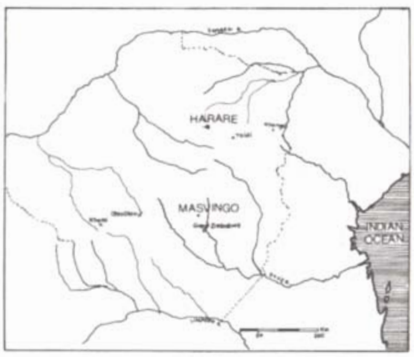


Figure 1: Patterns of Distress

(b) The doorways and step platforms which show multiple micro-fractures and flaking of the *daga* surface. This area is subjected to differential moisture and sunlight changes (Fig. 1c).

The permutation of cracks on all these areas varies with the general use of the structure.

The walls, which generally have a rough surface finish both internally and externally, do not usually suffer from surface flaking or microcracking. The most common symptoms of distress on walls are vertical cracks, which tend to correspond with the alignment of the internal timber framework. In serious cases of failure, blocks of *daga* collapse and expose the timber framework. Repair is normally done by replastering; the success of this depends on finding a suitable quarry with compatible material. In some cases, random deep cracks occur due to termite attack on the timber frame. If the cracks are threatening the stability of the structure, rebuilding is normally carried out. When the structure is abandoned, the thatched roof is usually the first to decay and collapse due to lack of maintenance. This exposes the underlying *daga* structure to the natural elements. The result is a ruin and, with time, the decaying *daga* will appear like a mound.



MAP I. South-central Africa showing sites and areas mentioned in the text.

Investigations on archaeological remains

After analysing the pattern of *daga* deterioration in contemporary vernacular architecture, the project then documented the decay in prehistoric structures. The purpose was to identify factors of decay caused by abandonment and those problems which could be attributed to constructional weakness and use-wear. All the surviving structures which were still above ground were located in regions with low precipitation and with soil formation of reddish granite clays (Table I, Map 1).

No	Site	Soil Type	Climate	Condition	Structure Type
1	Khami	red-brown clayey sands	hot/dry	above ground	plastered stone walls
2	"	"	"	"	floor and wall
3	"	"	"	"	floor and features
4	Dhlodlo	red-brown clayey sands	"	"	floors, walls and features
5		"	"	"	floors and walls
6	"	"	"	"	floor and features
7	Great Zimbabwe	grey clayey sands	hot/wet	above ground (badly eroded)	floors and wall
8	"	red sandy clay	"	excavated	floor and features
9	"	"	"	"	floors, walls and eroding features
10	Tsindi	brown-red clayey sands	"	"	floors and features
11	Nyanga	red sandy clay	cool/wet	reconstructed	complete houses with fittings

*Hot= above 18 C, Cool= below 18 C; Wet= above 800mm, dry= below 800mm

Table I: Distribution of prehistoric *daga* structures and their conditions

Although the prehistoric structures show some genealogical relationships with present-day structures, archaeological evidence indicates some subtle differences in their design and construction. The prehistoric structures were designed to last, and were more complex than the more recent single-compartment hut-dwelling synonymous with *daga* material.

The prehistoric houses were often divided into two or three compartments, with vernadahs, complex interior platforms and fittings. Some walls seem not to have incorporated a timber framework within the *daga* matrix and were non-load bearing. The roof was supported by the outside verandah posts. The non-load bearing walls were used to protect and divide interior space. The verandah sometimes had a low *daga* wall around it. The surface finishes for the wall and floor were similar, and at times decorated [4]. There is evidence of firing the *daga* structure in order to give it colour and durability.

The post-collapse appearance of prehistoric structures is characterised by a random heap of *daga* blocks, deep vertical and horizontal cracks, and a general loss of shape. In some cases, roots of plants have penetrated the cracked and eroding structures. The top section of the walls shows signs of weathering, with most of the edges eroding away. The interior surface of most of these curvilinear walls show signs of serious erosion, and the exterior surfaces exhibit a peculiar flaking towards the base of the wall (Figs. 2,3)

The failure patterns on the floors and internal fittings are similar to those in the pre-deposition structures except that the ravages of time make them appear worse. In areas where timber posts had been dug into the floor, undulating cracks have tended to develop radially (Fig. 1b). Besides these, randomly distributed cracks were noticed in most floors. Data obtained when monitoring these floor cracks by using levels and strain gauges suggested that they were not active, although they provide potential areas through which weathering and erosion agents could start the process of decay. The edges of the floors also showed signs of continuous decay due to micro-erosion and abrasion. With the newly excavated structures, microfracturing and flaking was a general phenomenon. These gave a rough and undesirable appearance to the fabric of the structure. The fired floors show no signs of this type of deterioration but are weak in compression (Fig. 4).

CURRENT RESEARCH INVESTIGATIONS

Pre-deposition cracks and patterns of failure in most cases seem not to exhibit movement. However, they tend to form zones of weakness which facilitate the development of subsequent processes of decay. These emanate from environmental fluctuations and lack of maintenance after abandonment. Current research has focused on experimental work and on the investigation of the chemical and mineralogical properties of the material in order to explore further the failures observed. Tentative results on the *daga* structures are beginning to give an insight into their failure mechanism.

The initial investigation into the chemical and mineralogical nature of the *daga* was carried out on samples from the Great Zimbabwe ruins. The aim was to investigate those physical and chemical properties which might contribute to the deterioration of the material. Samples from two structures which were representative of the possible types observed at Great Zimbabwe were analysed. The selection was based on colour differences of the grey and red/brown *daga*. Results of the mineralogical analysis indicate that the materials are from decomposing local granite (See Table II). Chemically the material has a high content of silica and alumina and also contains moderate amounts of iron and potassium. Chemical tests also confirm archaeological data which indicate two sources of quarrying for the *daga*. Firing of *daga* structures in order to achieve durability is also indicated by the deficiency in kaolin.

Experimental work shows that given a good quality of *daga* from historically known quarries, walls are primarily affected by construction design and climatic factors. The use of timber uprights introduces two problems: differential thermal coefficient of expansion of the materials and potential attack by termites. There are also difficulties when *daga* is used to plaster stone walls. Problems such as bulging associated with stone walls tend to lead to the detachment of the *daga* plaster. The *daga* walls which do not incorporate timber in their matrix are most seriously affected by the climate (See Fig. 5). Experiments with walls of different composition have shown that rainfall erodes the top surface area thereby forming gullies on the wall, which in turn leads to the creation of vertical channels. This decreases the tensile and compressive strength of the wall. The wetting and drying due to seasonal differences exacerbates the situation.

Minerals	grey *daga* samples	red/brown *daga* samples
quartz	51.3	40.0
kaolin	41.2	11.2
mica	0.8	30.0
felspar	4.3	3.5
iron/potassium oxides	2.8	2.5
Physical properties of all samples		
mean density	1.8g/ml.	mean porosity 33%
Size range of pores-microns	500	Approx. 40%
	500 106	11%
	106	49%
*pH Approx. 6.6 and soluble salts	.23%	

Table II. Approx. mineralogical/physical properties of *daga* samples from the Great Zimbabwe ruins [5].

The *daga* floor experiments were designed to explore different parameters since their deterioration patterns are different from those noticed on the walls. Different floor foundations with varying *daga* compositions were analysed in order to investigate the genesis of the random cracks noticed on prehistoric structures (Table III). Current data shows that floors on rock foundations manifest cracks which tend to align with the layout of the stones. When subjected to natural elements these cracks widen rapidly. Foundations with sandy soils tend to perform better than most and exhibit fewer cracks. A possible explanation for the occurrence of random cracks could be the collapse impact of the superstructure on to the floor, but this hypothesis needs more exploration

Foundation	Cracks Mean/m	Mean Width/mm	Mean Depth/mm	Ave Floor Movement/mm	Comment
Clay	25	2	3	-5	multiple cracks
sand	11	3	3	-3	few deep cracks
ash	15	1	-	-6	microcracks edges eroding
stones	22	4	5	0	wide cracks edges eroding

Table III. Behaviour of reddish sandy clayey *daga* with different foundations.

On excavated *daga* structures it has been shown that the development of microcracks and flaking takes place within the first ten hours of exposure to direct sunlight. It seems that it is not the temperature which affects the *daga* surface but rather the rate of drying. Attempts to repolish with cow dung have met with partial success. If applied regularly, it creates a membrane which in turn protects the *daga* surface from direct sunlight and some biological attack. The polish gives an authentic and aesthetically acceptable appearance. However, if the cow dung is not applied properly, it can encourage termite attack.

CONCLUSION

The aim of the present investigation of *daga* structures is to document the failure mechanisms and patterns of associated deterioration. The primary assumption is that in order to find a solution which can retard the deterioration, we must understand the genesis of the problem. Since we are dealing with the end-product of a protracted and complex process, a study of the symptoms of the problem may help to identify the causes of distress. Deterioration may manifest itself in particular forms and patterns. It is realised that the problems are not monocausal but, by trying to isolate the various factors which contribute to the decay of *daga* remains, we can begin to have an insight into possible remedies.

ACKNOWLEDGEMENTS

I am very grateful to Berzick Dube for helping me in the project and monitoring the experiments whilst I was away in York.

Fig. 2: Prehistoric structure-interior decay.

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Fig. 3: Prehistoric structure-exterior decay. Note flaking towards base of wall

Fig. 4: House floor with features- a month after excavation. Note random cracking and weathering.

Fig. 5: Experimental wall- after a year of exposure to elements of nature.

ABSTRACT

Adobe brick test walls were constructed in 1985 near the historic adobe ruins of Fort Selden in southern New Mexico to assess the performance of various preservation methods that could be used to protect the walls of the historic fort. The methods include: (1). use of chemical sprays and amended mud plasters to retard erosional rates of the vertical wall surfaces; (2). implementation of assorted treatments to the bases of walls to determine the rate in which the capillary rise of moisture can be affected; (3). and testing different types of wall caps to determine their effectiveness in protecting the tops of walls.

After five years of exposure, many of the tests implemented provided valuable results. Regular monitoring of this project will continue until 1995, at which time a comprehensive report on the test wall experiment will be compiled.

Key Words

TEST WALLS, AMENDMENTS, WALL CAPS, FOUNDATIONS, SPRAYS, EARTHEN ARCHITECTURE

Fig. 1 Test walls, looking west, southwest. The historic ruins and the visitor center are in the background.

Fig. 2 Test walls, looking east.

AN EVALUATION OF THE NEW MEXICO STATE MONUMENTS ADOBE TEST WALLS AT FORT SELDEN

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INTRODUCTION

In 1985, a series of adobe brick test walls were constructed 200 meters east of the historic adobe ruins of Fort Selden State Monument in southern New Mexico (figs. 1 & 2). These test walls were built to assess various preservation methods that could be used to protect the historic adobe walls at the Fort. A secondary purpose was to provide information to the public on how to better preserve historic walls made of earth. Three general research parameters were investigated: (1) the viability of using chemically amended mud plaster mixes and chemical sprays to protect vertical surfaces of earthern walls, (2) installation of various systems at the bases of walls to monitor capillary rise of moisture, and (3) the use of various capping techniques to protect the tops of walls.

The historic ruins of Fort Selden have been exposed to the elements without roof protection since 1891. When the military post was acquired by the State of New Mexico in 1972, it was developed for display and interpretation to the public. At that time a decision was made to leave the walls essentially as they existed without any reconstruction or erection of shelters. The site managers elected to maintain the historic walls through a process of regular maintenance of patching and recapping using mud. (For a description of the stabilization methods used on the fort and for more information regarding its history, refer to the paper by Thomas Caperton in this publication). Cyclical maintenance using unamended (that is, without chemicals or stabilizers) materials is an admirable approach and is the preferred preservation methodology for historic ruins. This approach to wall preservation would have worked at the site if sufficient staff were available to stay apace with the maintenance program. However, over the last ten years the cyclical maintenance program clearly could not keep up with the preservation needs, as significant loss of wall fabric was taking place. This motivated the test wall project in order that options other than frequent maintenance might be found.

TEST WALL DESIGN

The Museum of New Mexico State Monuments initiated the research effort with a literature search aimed at learning which methods had already been tested and reported. Consultation was then conducted with personnel from the preservation and adobe construction professions throughout the southwestern part of the United States. Some of the techniques that had provided positive results in other testing regimes were incorporated into this test wall project [1]. A few techniques that had failed in past preservation attempts were implemented in order to demonstrate the deleterious effects of such treatments. Since funds were limited, only a fraction of the innumerable methods and chemicals available to test were implemented in this experiment.

Detailed descriptions of the test wall plot that are not contained in this paper can be found in previous reports [2, 3]. Architectural specifications and drawings were produced by P.G. McHenry, AIA [4]. The adobe bricks and the soil used for the mortar and plaster in the construction of the test walls were all from the same source. The soil particle size of the adobe bricks is 63% sand, 19% silt, 18% clay (nonexpandable). The mortar used in the laying of the brick and for the plaster was tempered with washed sand to make a workable mix. What follows is a brief description of the New Mexico State Monuments adobe test wall design.

Amended Panels

Unamended mud plaster is the most compatible rendering material for earthen walls. The only problem with this type of wall protection is that, if left unsheltered, it requires frequent maintenance. Methods to retard the erosional rate of plasters have been tested and implemented for thousands of years. Preservationists today many times face a shortage of funds and time to maintain a structure properly using unamended mortar. For this reason they continue to seek a suitable amended rendering for earthen walls which retards the cyclical maintenance without compromising the wall by the effects of coatings that are too rigid, impermeable, or visually obtrusive.

Another ongoing endeavor has been the search for a compatible preservation material that can be sprayed or brushed onto an earthen wall without the use of a plaster coating.

In an attempt to identify certain naturally occurring amendments and manufactured chemicals that could be compatible with historic earthen walls, the following research design was implemented.

Two walls were constructed of adobe brick and mortar. Each wall is 19.8 meters long (65 feet), 1.52 meters high (5 feet), and 24.4 cm wide (10 inches). One wall was set on a north/south axis and the other on an east/west axis. Each wall face is divided into thirteen panels, 1.52 meters (5 feet wide). There are twelve amended panels on each wall face with one panel of unamended mud which serves as a control (fig. 3). The four wall faces are the same. The amendments are applied to both sides of the wall, opposite each other, including the wall top. Each amendment and control panel has a north, south, east, and west exposure. Thus the effect of climatological conditions, including storm patterns and solar orientation, can be assessed for each panel.

Fig. 3 Amended wall, south face, looking west/northwest. Panel with straw is on the right.

The treatments used include amended mud mixes applied as plasters and sprays and roll-ons, which were applied directly to the wall surface.

The amended mud plaster was applied in three coats to a total thickness of 2.54 cm (one inch). Each of the amended panels was divided in half on a vertical axis. One half of the panel was treated with a 5 percent solution and the other with a 10 percent solution of the chemical amendments. The different solutions of the same amendment will be used to determine the minimal amount needed to be cost effective when used for retarding the erosional rates of plaster. Refer to Table I for a description of each amendment, its history of use, and its present performance in this project.

Like the amended mud plaster panels, the panels used for the spray and roll-on experiments were divided in half on a vertical axis. One half of each panel was plastered with three coats of unamended mud and the other half was left unplastered. These panels are being used to assess the effectiveness of spray and roll-on applications on mud plastered and unplastered earthen ruins, such as the ones at the adjacent fort. Chemical amendments were either rolled or sprayed on both halves of the panel at equal strength. Refer to Table II for a description of each amendment, its history of use, and its performance to date in this project.

Fig. 4 Example of test wall constructed with concrete wainscot installed along the base.

Wall Base Experiments

Various methods have been used throughout history to retard the capillary rise of moisture into earthen walls. Some have proven beneficial and some detrimental to the preservation of wall bases.

Twelve walls, each with a different type base, were constructed as part of this project to assess the effects of capillary rise (fig. 4). Each wall is 1.52 meters high (5 feet), and 25.4 cm wide (10 inches). The various types of wall treatments were selected upon the basis of modern and historic practices. Some of the techniques used are known to be detrimental to the preservation of earthen walls but were used in this experiment to show graphically through time their effects on the wall bases. Refer to Table III for a description of each wall base design.

Each wall contains eight electrical resistance sensors, which provide data on relative moisture contents within the wall. The readings are taken with a resistance meter (Soiltest Moisture Temperature Meter (R), model - 300B).

Wall Cap Descriptions

In many parts of the world, a wide variety of ways have been used to protect the tops of exposed earthen walls [5]. Many of the methods used are ones that protect yard or corral walls that were never built to be covered by a roof overhang. Other methods have been developed to protect the tops of archaeological ruin walls built of earth. Some have been successful and some have not. One of the goals of this test wall project is to assess the performance of various techniques used to cap walls.

Fig. 5 Wall cap experiment, looking northwest.

Four different wall caps, each 1.52 meters long (5 feet), were applied to an unamended adobe wall 6.1 meters long (20 feet), (fig. 5). The types of capping materials used are commonly found in New Mexico. The four wall caps are: (1) A course of adobe bricks stabilized with asphalt emulsion placed on top of and flush with the wall, (2) a course of adobe bricks stabilized with asphalt emulsion placed on top of and perpendicular to the wall face, thus creating a 5.1 cm overhang on each side of the wall sloping to the north, (3) a rounded cement cap troweled on to the top of the wall, and (4) three courses of fired brick applied to the top of the wall to form a denticulated cap.

MONITORING PROGRAM

A comprehensive photographic monitoring program is being conducted for each test wall panel. Black and white photographs and color slides have been taken from established datum points every two months since testing began in 1985.

Relative moisture readings from the wall base experiment were taken after

Table 1
Amended Mud-Plaster Mixes

Amendment	Composition	Previous Uses	Test Condition
El Rey Superior 200 (basically Rhoplex E-330 with a debubbling agent addded)	methyl methacrylate/acrylate resin at 47% solids in water	Rhoplex MC-76 and Rhoplex E-330, almost identical to El Rey Superior 200, have been used at Chaco Canyon, Aztec, and Wuptaki National Monuments to repoint masonry walls for up to 15 years	little erosion, with the 5% solutions showing slightly more than 10% solutions; slightly darker than unamended plaster
Soil Seal Concentrate	latex acrylic balanced with copolymers prepared in emulsion form; consists of 40% polyethoxylated ethanol and 3.5% silicates; it is 46% solids in water	used commercially for soil surface erosion control, it had been used as a soil stabilizer in adobe bricks, mortar, and repointing of masonry walls at Pecos National Monument in the 1970's	moderate erosion, with 5% solutions showing slightly more erosion than 10% solutions; slightly darker than unamended plaster
Daraweld-C	high polymer resin emulsion at 51% solids in water	used commercially as a bonding agent for concrete; used by National Park Service in adobe preservation but use has ceased due to its relative impermeability	little erosion, with 5% solutions showing slightly more than 10% solutions; the 10% solution is slightly darker than unamended plaster; the 5% solution shows no color change
Asphalt Emulsion	petroleum-based product	since the early 1940's a popular amendment for stabilized brick in construction; also used somewhat in the southwest as a mud-plaster amendment although its relative impermeability over unamended mud-brick walls inhibits evaporation	little to moderate erosion, with similar rate for 5 and 10% solutions; much darker than unamended plaster
Agave juice	extracted from boiled agave leaves, the pulp is pounded and the extract steeped for 2-3 weeks	has been used by some desert cultures as an adobe plaster amendment	moderate to serious erosion; no color difference from unamended plaster
Straw	4 1-lb. coffee cans of straw cut into 2-inch lengths were mixed with 1 wheelbarrow of mud	used universally as a mud-plaster amendment; promoters claim that it acts as a binder to reduce cracking on wall surfaces, critics claim that it encourages moisture penetration and is a food source for insects which then enter wall	moderate to serious erosion; termites have created "tunnels" through the mud plaster on the north face accelerating its erosion

Table 2
Amended Spray and Roll-On Applications

Amendment	Composition	Previous Uses	Test Condition
Acryl 60 base coat and Super Quickseal finish coat, used in this sequence because of manufacturer's recommendation (roll-on application)	Acryl 60: acrylic polymers and modifiers, designed as an additive to Portland cement to improve adhesion and mechanical properties Super Quickseal; cement-base coating, a commercial finish coat for masonry and concrete	Acryl 60 had performed well in 3 years of use at Bent's Old Fort	the Acryl 60/Super Quickseal combination has experienced moderate erosion; color can be matched by manufacturer
K & E Penetrating and Hardening Mineral Sealer	Inorganic mineral salts at 30% solids in water	at Bent's Old Fort experienced little erosion after 3 years exposure	moderate to serious erosion; no color change from unamended plaster
Linseed oil	1 part linseed oil: 5 parts mineral spirits	used somewhat in adobe-plaster preservation and in mud-floor consolidation; used at Bent's Old Fort in a 1:2 solution and showed very little erosion	moderate to serious erosion; darkened the wall surface
Silicote	modified silicone resin spray at 9.9% solids in xylene	not known if it has been used in adobe preservation	moderate to serious erosion; no color change from unamended plaster
Seal-Krete	a commercially manufactured acrylic for waterproofing stucco, masonry, cement and mud brick	not known if it has been used as a spray on adobe or mud plaster	moderate to serious erosion; no color change from unamended plaster
Thorocoat (roll-on application)	a ready-mixed non-cementitious 100% acrylic-textured coating for protecting and decorating a variety of exterior and interior surfaces	mud-brick preservation uses not known but manufacturer claims that its thickness allows cracks and pores to be water resistant and to release moisture	moderate erosion although most is located where settlement cracks have occurred; color can be matched by manufacturer

Table 3

Types of Wall Bases

1.	Standard concrete foundation with stem wall, and a cement stucco over wall surface
2.	Rock foundation with mud mortar and exposed adobe wall surface
3.	Base course (a varied grade of rock and soil used for highway underlayment) foundation with exposed adobe wall surface
4.	Unamended adobe foundation with exposed adobe wall surface
5.	Unamended adobe foundation surrounded with sub-surface polyethylene sheeting sloping away from the wall to provide a drainage gradient; the wall has an exposed adobe surface
6.	Unamended adobe foundation surrounded with a sub-surface layer of mud amended with Union Carbide R-274 (a silicon base water repellent) sloping away from the wall to provide a drainage gradient; the wall has an exposed adobe surface
7.	Unamended adobe foundation with perforated plastic pipes set on each side of it in gravel which drain into a rock filled sump; the wall has an exposed adobe wall surface
8.	Unamended adobe foundation with cement stucco over the wall surface
9.	Unstabilized adobe foundation with a poured and formed concrete wainscot, exposed adobe wall surface
10.	Rock foundation with mud mortar and a poured and formed concrete wainscot, and exposed adobe wall surface
11.	Unamended adobe foundation with unamended mud plaster on the wall surface
12.	Unamended adobe foundation coated with parge plaster and asphalt vapor barrier, exposed adobe wall surface

Table 4

Erosion Ratings – Amended Panel Test Walls

After 4 years and 4 months exposure:

Very little erosion = 5
Little erosion = 4
Moderate erosion = 3
Serious erosion = 2
Very serious erosion= 1

#	Treatment	Wall Direction				
		N	S	E	W	Avg.
1.	Control Panel	2	2.5	2.5	1	2
2.	El Rey Superior 200	4	4	4	4	4
3.	Daraweld – C	3.5	4.5	4	3.5	3.9
4.	Asphalt emulsion	4	3.5	4	3.5	3.7
5.	Super Quickseal/Acryl 60	3	3.5	3	3	3.1
6.	K & E Mineral Sealer	2	2.5	3	1.5	2.2
7.	Linseed Oil	2	2.5	2.5	2.5	2.4
8.	Thorocoat	3.5	4	2	3	3.1
9.	Agave juice extract	2.5	2.5	2.5	5	3.1
10.	Soil Seal Concentrate	3	3.5	3.5	2.5	3.1
11.	Silicote	3.5	2.5	2	2.5	2.6
12.	Seal-Krete	2.5	2.5	3	1	2.2
13.	Mud w/straw	3	3	2.5	1	2.3
	Severity of exposure direction	38.5	41	38.5	34	
	Averages	3	3.2	3	2.7	

every measurable precipitation for the first two years of the project.

Munsell Soil Color analysis of amended walls is conducted on an annual basis.

Erosional profiles of the chemically amended panels will be recorded in 1995. During wall construction in 1985, small aluminum pins were inserted perpendicular to and flush with the panel surfaces. The pin ends serve as reference points for the recordation of erosional profiles.

Temperature and precipitation records have been maintained to provide the environmental information necessary to evaluate the performance of the test wall experiments.

OBSERVATIONS

It should be stressed that the results of this experiment to date are specific to the particular conditions of the site. These include soil particle size and mineralogical content of the soil used in the manufacture of the adobes and mortar, application technique, and climatic conditions that existed when the treatments were applied and that have existed since. What is reported to have favorable or nonfavorable results in this test wall experiment may provide different results under other conditions. Recommendations, however, can be made for further testing based on the positive results reported in this paper. The test walls have provided interesting results since they were constructed five years ago. Refer to Table IV for each panel's condition and to (Fig. 6) for examples of erosional rates.

Rainfall at the site has been above normal since 1985, averaging approximately 30 cm (12 inches) of rain per year. The greatest amount of precipitation occurred in August 1988 when 13 cm (5.2 inches) of rain fell, 5.1 cm of which fell within two hours. There have been some fairly significant accumulations of snow on the walls. One storm deposited .61 meters (2 feet) of snow. The subsequent freeze/thaw action from this moisture contributed greatly to the deterioration of the walls. Storm patterns seem to be predominately from the west, southwest, and northwest.

Amended Panels

The west faces of the amended panels are generally eroding faster than the other faces (fig. 7). The south faces of the panels are generally eroding slightly less than the north and the east faces (fig. 3). This can be attributed to the prevalent storm patterns which exist at the site. In addition, the north faced wall panels exhibit more deterioration at their bases than the other three exposures, due most likely to the lack of sun which slows the melting of accumulated snow and the evaporation of accumulated rain. During periods of freeze/thaw, this type of lingering moisture will cause accelerated failure of the wall and plaster fabric.

The amended wall tops have generally cracked and begun to fail at various rates, much more so than the treated vertical faces. This pattern is expected to some extent because of the exposure of the horizontal wall top to falling rains and accumulating snows.

The 5 percent solutions of amended mixes have generally eroded slightly more than the 10 percent solutions, with the exception of the agave juice and asphalt panels which seem to be failing at approximately the same rate.

Of the amended plaster mixes tested, El Rey Superior 200 (Rhoplex E-330) and Daraweld-C have proven so far to be the most favorable in providing a rendered protection. It should be pointed out that in many circumstances, especially when dealing with an archaeological site, plastering an earthen wall to provide a sacrificial coating may not be aesthetically pleasing and will obscure certain attributes of a wall such as the earthen brick coursing or pise levels. In cases such as these, other preservation methods may be deemed more appropriate, such as capping the walls using sufficient drip edges or construction of shelters.

It is recommended that further tests be conducted using Rhoplex E-330 and Daraweld-C as amended mixes for plaster. Rhoplex E-330 should be used instead of Rey Superior 200 because the straight Rhoplex will not darken the mortar as does the El Rey Superior 200, which has been amended by the manufacturer with a de-bubbling agent. The 10 percent solutions (1 part amendment to 5 parts water ratio) are providing sufficient protection to the unamended wall for the first five years of exposure. It is estimated that a wall plastered with these percentages of amendment would have to be replastered every ten years. Caution should be taken in using these types of amendments on historic resources without further testing, however.

It is also recommended to test many more of natural occurring amendments that were evaluated only briefly in this project. If proven effective, and in many parts of the world they have, naturally occurring amendments are most often

Very little erosion.

Little erosion.

Moderate erosion.

Serious erosion.

Very serious erosion.

Fig. 6 Examples of Erosion rates.

easily obtainable and much less costly. The agave juice extract should be researched more as to how long the juice is left to steep, what the ideal concentrations would be, etc. Amendments such as prickly pear cactus juice, lime sprays, and charcoal should be investigated further [6].

Both the straw-amended panels and the control panels are eroding faster than the amended mix panels. The panels amended with straw have eroded slightly less than the control panels. The erosional patterns for these panels are even throughout the vertical face without developing large voids or cracks, which are evident on most of the amended spray and mix panels. This even, sheet-type of erosion is visually much more pleasing than the amended panels.

Fig. 7 Amended wall west face. Control panel is on the right.

The sprayed and rolled-on applications are generally eroding more than the amended mud mix applications. In fact, most of the sprayed panels have eroded faster and created more damage to the adobe substrate than the control panel. The erosional patterns of the sprays can be characterized by large gouged areas that have developed in the vertical face where runoff moisture is directed into weaker areas. The water-based sprays have penetrated only about 1 millimeter. None of the spray applications have performed well.

The Super Quickseal roll-on exhibits considerable checkered cracking (see fig. 8). Thorocoat has begun to crack, allowing moisture to enter (fig. 9).

It is not recommended to experiment with or use any of these sprays on earthen ruins. However, there do exist solvent-based, monomer and low polymer type sprays that have proven effective in preserving earthen architecture. For more information on these type of sprays, refer to the article by Agnew et al., in this publication.

Wall Base Experiments

The twelve walls that were built with various types of wall base treatments are providing less information than hoped. The readings from the sensors were taken for a period of two years, then stopped because the data obtained was minimal. However, the data did indicate that the two walls with concrete wainscots and the two walls with the cement stucco renderings are retaining more moisture above grade than the other wall-base treatments.

The failure of the moisture sensors to provide more data may be attributed to (1) lack of sufficient levels of moisture to be monitored, and/or (2) improper instrumentation used to obtain the relative moisture readings. The instrumentation used for this experiment does not provide quantitative data on percentage moisture content. Other nondestructive means to obtain measurable moisture readings should be investigated.

Fig. 8 Detail of the erosional pattern on the Super Quickseal panel.

The wall-base experiment is, however, beginning to exhibit differential rates of erosion at the bases of the walls. Even though these erosional rates are presently very subtle, it is anticipated that within a few years definite correlations can be made between basal erosion and the various techniques used at the bases of the walls.

Wall Caps

The four different types of caps installed on the 6.1 meter-long test wall are providing some interesting results. All four wall caps, including the one with an overhang, are experiencing accelerated erosional patterns at the interface between the cap and the top of the unamended wall. This is anticipated to some extent since rain quickly runs off the fairly impervious caps and is directed into the top of the unamended wall where the moisture can penetrate.

Fig. 9 Thorocoat panel. Note cracks and deteriorating coating.

The cap with the overhang is failing in part because the south overhanging portion which slopes to the north has no drip edge, causing water to run back under the overhang and penetrate the unamended wall top. On the north side of this same cap, moisture is eroding the unamended wall top, probably because the overhang does not extend out sufficiently away from the wall. The important question here is how much do• impervious caps, similar to the ones used here, protect the wall tops, as compared to leaving the wall tops exposed with no protection. When comparing the loss of the top of the walls between this wall cap experiment and the top of the uncapped walls in the wall base experiment, some useful conclusions can be drawn. First, the caps have indeed protected the tops of the walls. Approximately 3 cm of wall top has been lost from the uncapped walls, whereas no loss in height of the wall has occurred on the capped walls. What is interesting, however, is that the wall that has been capped has lost considerably more vertical wall surface on the upper portion of the wall, just below the interface between the cap and the unamended wall, than the uncapped walls. Comparisons in upper wall thickness between uncapped walls and this capped wall indicate that as much as 3 cm of vertical wall fabric has been lost.

Thus it seems that the installation of fairly impermeable caps without proper drip edges on unrendered walls may not be sufficiently beneficial. In this experiment, the caps have protected the tops of the wall but have accelerated vertical wall deterioration. Uncapped walls have lost material from the top but seem to exhibit less fabric loss on the upper vertical surfaces. Long-term monitoring of this wall cap experiment needs to be conducted in order to determine how much, if any, the wall caps will protect the walls as compared to those that do not have caps.

It is recommended that more experimentation be done utilizing caps that have sufficient overhangs extending out away from the wall. These overhangs should provide drip edges that will prohibit moisture from flowing back into the structure. Monitoring the splash effects at the base of such treated walls should also be conducted.

CONCLUSIONS

To date, the test wall experiment has yielded results that can justify further testing of some of the techniques used in this program. The project has also graphically shown which technique should not be considered to be used on historic earthen walls.

Since the construction of these walls in 1985, the Getty Conservation Institute has entered into a major testing program with new walls built adjacent to Fort Selden State Monument test plot. The Getty's program includes testing chemical consolidation of walls, shelter designs, drainage techniques, and structural reinforcement designs. The research of these two institutions is expected to yield important insight into how to better preserve historic earthen architecture.

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