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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Preservation of Historic Adobe Structures— A Status Report

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The physicochemical and mechanical properties of adobe soils and building materials, and the technology of preserving historic adobe structures have been critically reviewed. In most cases, the deterioration of adobe structures can be directly or indirectly correlated with the presence of excess moisture. Therefore, the successful preservation of most historic adobe structures depends largely on effectively protecting these structures from water. This review indicates that the technology of preserving adobe structures needs further development to ensure the longevity of the structures.

Areas in which research is needed have been identified and include: (1) the development of standard methods to characterize the composition and physical properties of adobe soils, and the mechanical properties of adobe brick; (2) nondestructive methods to measure the water contents of and water movement in adobe structures; and (3) the evaluation of the effectiveness of different types of preservation materials and methods.

Key words: Adobe building materials; adobe soil; mechanical properties; moisture determination; preservation technology.

1. Introduction

This report is based on a critical literature review of the composition, physical properties and durability of adobe[1/] building materials, and of methods used to preserve adobe structures. Adobe building materials, which include sun-dried brick, adobe mortar and cast adobe, are constituents of many of the historic structures in the arid southwestern region of the United States which federal, state, and private organizations are endeavoring to preserve. This review was carried out under the auspices of the National Park Service to assess the current status of adobe preservation technology and to form the basis for future preservation programs.

Numerous reports and books have been published on adobe and related building materials and several large bibliographies are available [2-4]. The majority of these publications, however, are directed towards new construction e.g., references 6-7, with only a small number of them addressing the preservation of old structures. Recently, the preservation problems associated with adobe structures have attracted increasing attention, both in the United States [7] and abroad [8]. Because of this increased interest a symposium has been held recently in Iran devoted exclusively to the preservation of mud-brick structures [9].

1/ Adobe is defined as any type of clay soil which, when mixed with water to a plastic consistency, can be made into a part of a structure [1].

Adobe and related materials are among the oldest building materials on earth, with rammed earth[2/] construction dating back to Neolithic times (3,000 to 10,000 B.C.) [10]. The "Tower of Babel" was apparently constructed with adobe brick [11]. Under favorable conditions, earth structures of this type can be extremely durable. For example, portions of the Zigguart of Agar Quf, which are over 2,000 years old, still exist in Iran [12].

Houses are still being built with adobe brick and rammed earth building materials (often stabilized with bituminous materials). However, despite mankinds' long use of earth as a building material, this review indicates that the technology of preserving adobe structures still needs further development to ensure their longevity.

The reader must be cautioned that it is difficult to quantitatively compare the results of various studies because of the lack of uniformity in preparing test specimens and because of variations in test methods and test conditions. It is strongly recommended by this author that standard test methods, including specimen preparation, type of testing equipment, testing conditions, and methods of reporting the data, be established so that the results from different laboratories can be compared directly.

2. Composition and Properties of Adobe Soils[3/]

The composition and properties of adobe soils and building materials, including some remarks on rammed earth walls, are discussed in this section. Only brief reference to stabilized adobe is given because this material is the subject of the following chapter.

Primarily, attention is given in this section to the factors which appear to have the greatest effect on the performance of the adobe building materials and, therefore, on the durability of historic adobe structures.

2.1 Compostion and Moisture Contents of Adobe Soils

Certain types of soils appear to produce more durable adobe building materials than do others. Several investigators [13-16] have suggested that the performance of adobe soils are largely dependent on their particle size distributions. The following, therefore, is a brief discussion of particle size classifications of soils and of the textural classification of soils. Soil particles are usually classified as sand, silt, or clay based on their size. Good adobe soils contain only a small amount of gravel particles. Based on the particle size classification established by the International Society of Soil Science [17], particles in the range of 2 to 0.02 mm are sand particles; particles in the range of 0.02 to 0.002 mm are silt particles; while those smaller than 0.002 mm are clay particles[4/].

2/ Rammed earth is a mixture of sandy clay soil and water of a slightly moist consistency enabling it to be compacted between shuttering for monolithic walls or in molds for making individual blocks [1].

3/ Adobe soils denote soils which have been used to make adobe structures or soils which appear to have the necessary properties for making durable adobe building materials.

4/ Several other principal particle size scales exist, which differ slightly; for example, according to the particle size scale of the Federal Highway Administration, the size ranges are 2 to 0.05 mm for sand, 0.05 to 0.005 mm for silt, and particles less than 0.005 mm are classified as clay particles [17].

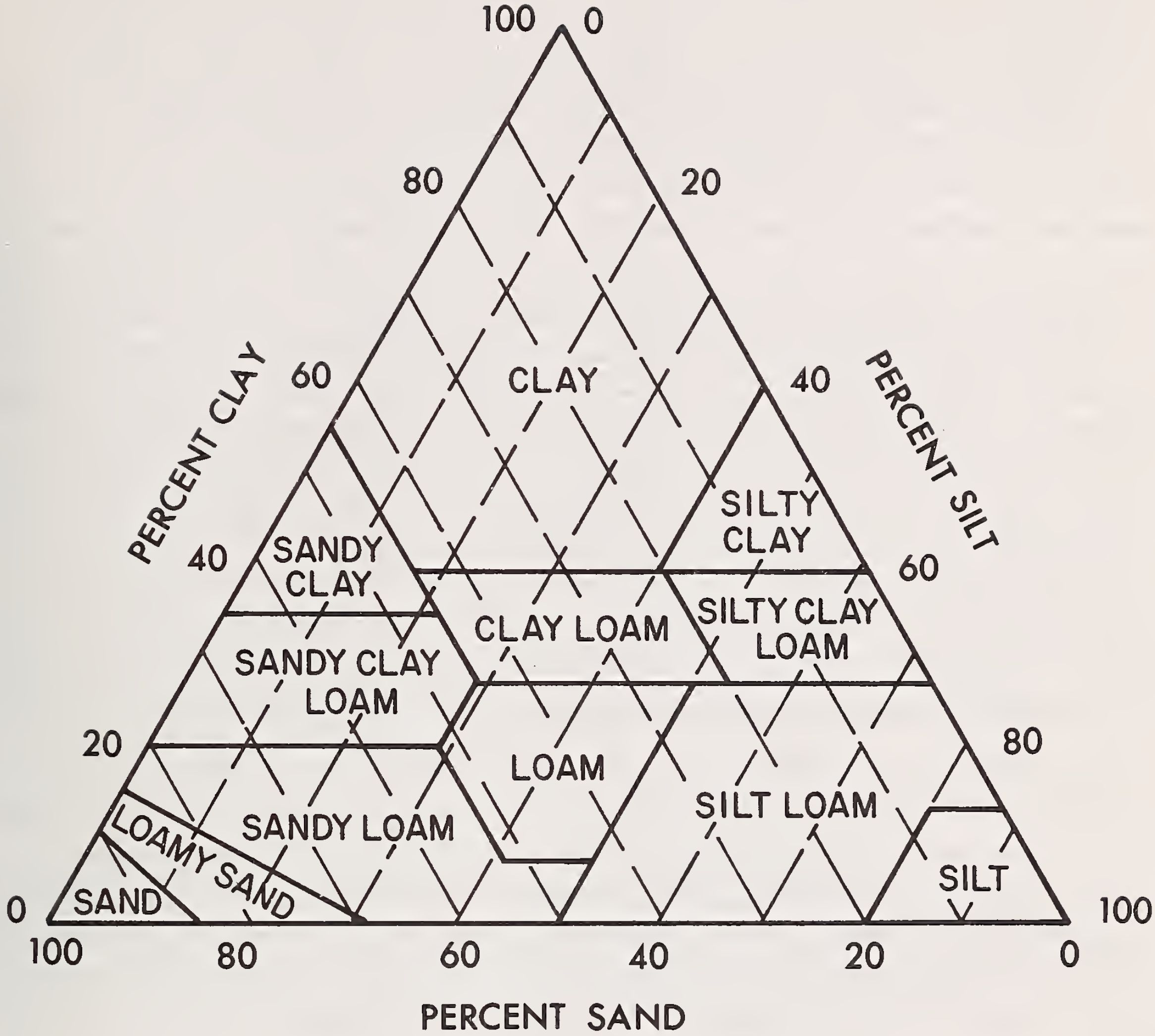

Figure 1. Chart of Soil Textural Classes

Soils are often separated into textural classes corresponding to different proportions of sand, silt, and clay as shown in figure 1. The clay portion, and to a lesser extent, the silt portion of a soil acts as the binder. A good adobe soil should contain sufficient quantities of clay and silt to form a matrix in which the sand particles are firmly embedded. Furthermore, the sun-dried material should be cohesive [18]. It is the clay portion of a soil which is primarily responsible for both its expansion, through absorption of moisture, and its shrinkage due to dehydration. A dimensionally stable adobe soil (defined as an adobe soil in which little dimensional change takes place between the wet and dry state), therefore, often has a high sand content [13]. Fenton has suggested [19] that a stable adobe soil should contain about 70 percent sand by weight. Schwalen [14] prepared satisfactory adobe brick from soils containing 9 to 28 percent clay. He also associated shrinkage and cracking of adobe bricks with high clay contents. Other investigators have confirmed the negative effects of high clay contents on the stability of adobe bricks and have suggested that soils for adobe bricks should contain between 70 to 80 percent sand and 20 to 30 percent silt and clay [16, 18-19]. In general, a soil should contain equal amounts of silt and clay [14]. Similar results were obtained by Patty [20] in a study of soils for rammed earth construction. He determined that soils should contain over 75 percent sand for satisfactory weather resistance. In addition, he observed that the size distribution of the sand particles had little effect on the resistance of the rammed earth walls to water erosion. Soils which contain high amounts of clay and silt can often be mixed with additional amounts of sand to produce a satisfactory mixture for making adobe brick [13, 19].

Based on the fracture characteristics of soils, Chang [21] developed a method to predict if a soil possesses typical adobe behavior. He observed that many soils will crack into large, irregular blocks upon drying. These primary blocks may fracture further to produce secondary macroaggregates having diameters in the range of 2 to 10 cm. If these macroaggregates have smooth cleavage planes and angular edges, the soil should be suitable as an adobe building material. He also postulated that soils containing either montmorillonitic clays or properly dispersed kaolinitic clays tend to have the properties typical of adobe soils.

The proper amount of water needed for making adobe bricks and rammed earth walls appear to vary with the soil. Fenton [19] suggested that for each adobe soil there exists a certain water content that will give the maximum density and strength. Long [22] recommended that an optimum amount of mixing water is 25 to 30 percent, on an air-dry soil basis, for adobe brick and 12 to 15 percent for rammed earth work. The proper amount of mixing water, however, depends on the clay and silt contents of a soil. For example, the optimum mix water for an adobe soil with 9 percent clay was found to be 14.3 percent and was increased to 30.8 percent for an adobe soil with 28 percent clay [14]. The moisture contents of sun-dried adobe brick also vary with their clay contents but usually are in the range of 1 to 3 percent [11, 14-15].

The magnitude of shrinkage accompanying the sun drying of adobe brick largely depends on the clay content, the type of clay, and the amount of mixing water. Schwalen measured volume shrinkages ranging from 0.4 to 7.7 percent for adobe bricks prepared from 10 different soils whose clay contents ranged from 9 to 28 percent [14]. Webb et al. [15] observed that drying shrinkage is not a linear function of the amount of mixing water; the amount of shrinkage increases considerably for higher water contents. They measured shrinkages ranging from 0.17 percent to 1.1 percent when the optimum amounts of mixing water were used. The addition of excessive mixing water in the production of adobe brick can cause significant shrinkages; for example, shrinkages as high as 37 percent have been reported [23].

Fenton [19] studied the effect of moisture contents on the shrinkage of sun-dried compacted cylinders of rammed earth prepared from a soil containing 46.7 percent sand, 32.6 percent silt, and 20.7 percent clay. Shrinkages ranged from near 0 percent, if the moisture content was less than 10 percent, to about 2.5 percent at a moisture content of 19 percent.

Eyre [13] has suggested that the strength and durability of adobe brick is affected by its pH and that each adobe soil has an optimum pH. He further suggested that if necessary, the pH of the adobe soil can be adjusted to its optimum value by additions of appropriate chemicals. However, he did not investigate the relationships between pH and the properties of adobe brick. Little, if any, other work has been carried out on the effect of pH on the properties of adobe soils except to measure their pH's. Read et al. [18] reported that the pH of eight adobe soils from Ellis County of Kansas State ranged from 7.15 to 7.67. Kriegh and Sultan [24] found the pH of four adobe soils from the southwestern region of the U.S. to range from 7.3 to 8.0.

All of the adobe soil analyses given in the reports covered by this review are incomplete in some respect. Usually the particle size distribution was given, but only a few qualitative determinations by x-ray diffraction of the major and minor components of adobe soils have been reported [24]. An adequate analysis of adobe soil should include at least the chemical and phase composition, particle size distribution, pH, moisture contents, and porosity. The porosity is important because of the strong relationships which exist between it and both the mechanical properties and the capillary potential of soils [17, 25-26]. A mercury porosimetry method of measuring soil porosity has been described by Sridharen et al. [27]. Other fundamental properties such as the plastic limit[5/] and liquid limit[6/], should also be determined. Methods for measuring the plastic and liquid limits are given in ASTM D423 [28] and D424 [29], respectively.

5/ Plastic limit is that moisture content in percent of dry soil weight at which the soil changes from a solid to plastic state [11].

6/ Liquid limit is that moisture content in percent of dry soil weight at which the soil changes from a plastic to a liquid state [1].

2.2 Physical Properties of Adobe Brick

A wide range of values for many of the physical properties of adobe brick are given in the literature. This variability in the data is understandable when taking into consideration the differences in composition of adobe soils, methods of fabricating adobe brick (the consolidation process is especially critical), the quality of workmanship, etc.

The dimensions of adobe brick appear to depend largely on the convenience of the user. Some reported dimensions of adobe in historic structures have ranged from 9 x 5 x 5 inches (23 x 13 x 13 cm) to 16 x 5 x 5 inches (41 x 13 x 13 cm) [10]. The size of adobe brick used for research purposes depends on the specific property being measured. Reported values of the density [11, 13-15] of dried adobe brick range from 98 to 125 lb/ft^3 (1570 to 2000 kg/m^3) and increase with higher sand contents.

Eyre [13] reported that the coefficient of thermal expansion for adobe brick made from 5 different soils ranged from 0.90×10^{-6} to 3.0×10^{-6} in/in per °F (0.50×10^{-6} to 1.7×10^{-6} cm/cm per °C). Webb et al. [15] found that the coefficients of thermal expansion of adobe bricks made from 40 different soils ranged from 11.1×10^{-6} to 14.2×10^{-6} per °C. The reason for the large differences between the two sets of data is not clear.

The expansion of oven-dried (105°C) adobe bricks exposed to a combination of 30 and 60 percent relative humidities were measured by Webb et al. [15]. Brick specimens made from a "clay soil" expanded by 0.24 percent when exposed for 25 days to 30 percent relative humidity followed by exposure to 80 percent relative humidity for an additional 25 days. In contrast, specimens made from a "sandy soil" expanded by only 0.012 percent after exposure to the same conditions.

Whittemore et al. [30] reported that adobe brick and rammed earth have thermal conductivities (K) of 10.7 and 11.3, respectively. These values are higher than for many other common building materials. For example, the K value for building gypsum is approximately 3 and between 6 to 9 for normal weight concrete [31]. The apparent insulating effect of adobe brick and rammed earth walls, therefore, can be attributed to the thickness of the walls rather than to low thermal conductivities.

Various types of water permeability tests have been carried out on adobe brick and rammed earth walls. Most of these tests are based on measuring the time required for moisture to penetrate a specific thickness of material. A form of the water permeability test developed for masonry walls [32] is probably the most reasonable method for measuring the resistance of adobe brick walls to rain. In this test, wall specimens are exposed to water spray at controlled flow rates and the time for moisture to penetrate the wall is measured. Furthermore, the resistance of the adobe brick wall to rain erosion can be visually evaluated. Whittemore et al. [30] measured water permeability using a water flow rate of 40 gal/hr (.15 m^3/hr). They observed that in about 0.03 hr. water was visible on the back surface of a 12 inch (30 cm) thick adobe brick wall. If the adobe was previously stabilized, however, with a 5.6 percent (by dry soil weight) bituminous admixture, the time required for penetration was increased to 18 hours.

Tests have been developed to simulate the penetration of adobe brick by ground water through capillary action. In general, test specimens are placed just in contact with water and the rate at which the water rises in the adobe is measured [13, 18]. Eyre [13] found that the height at which water rose in different adobe specimens by capillary action after 10 minutes ranged from 0.55 to 1.60 inches (1.40 to 4.06 cm). The effects of various admixtures were also investigated. The lowest absorption rate of 0.18 inches (0.46 cm) in 10 minutes was obtained with a mixture of 40 grams of soap, 80 grams of lime, and 650 ounces (1.84 kg) of adobe. The compressive strength of bricks made from the mixture, however, was only about 50 percent of the strength of the unadulterated adobe. The capillary rise of water in adobe mixed with 10 percent by weight of portland cement was 1.25 inches (3.18 cm) in ten minutes, compared to 0.55 inches (1.4 cm) in the unadulterated adobe. However, it is well-documented that addition of portland cement to soil has a positive effect on the resistance of adobe brick to water damage [19, 30, 33-34]. Webb et al. observed that the initial rate of water adsorption of soil cements was of the same order as that of burnt brick but decreased with time of exposure [15].

2.3 Mechanical Properties of Adobe Brick

A wide range of compressive strength values for cured adobe brick is given in the literature. Schwalen [14] reported compressive strengths to range from 332 to 544 psi (2.29 to 3.75 MN/m^2) for adobe brick made from 10 different soils. Eyre [13] obtained values ranging from 325 to 736 psi (2.24 to 5.07 MN/m^2) for four different adobe bricks. Long [22] measured the compressive strength of adobe brick prepared from six soils that ranged from a sandy loam to a silty clay loam. Their compressive strengths ranged from 60 to 785 psi (0.41 to 5.41 MN/m^2). Other investigators have reported [11, 15, 30] strength values in the range of 300 to 700 psi (2.07 to 4.75 MN/m^2).

Webb et al. [15] observed that the compressive strength of adobe brick increases with age. For example, the strength of one series of adobe brick increased from 250 psi (1.72 MN/m^2) after 7 days to 599 psi [4.13 MN/m^2) after 28 days. This 28 day strength decreased to 284 psi (1.96 MN/m^2) if the adobe brick was in a "wet state" (the term "wet state" was not defined nor is it certain that the environmental conditions were well controlled). Patty [20] observed that the compressive strengths of three series of rammed earth blocks increased from 437, 372, and 353 psi (3.01, 2.56, and 2.43 MN/m^2) after 6 months to 570, 581, and 497 psi (3.93, 4.01, and 3.43 MN/m^2), respectively, after 2 years.

Other factors which were found to affect the compressive strength of the adobe brick include the composition of the soil, the amount of mix water used in making the adobe brick, density of the dried brick, and the size of the test specimens. The effects of these factors are briefly discussed in the following. The 28 day compressive strength has been found to increase with increasing clay contents of the adobe soil until the optimum clay content is reached, thereafter, shrinkage cracking causes reduction in the strength [11]. As the adobe brick ages over a period of years, the effect of the clay content on the strength appears to diminish [20]. The compressive strength increases slightly with the fineness of the soil [13]. It has been firmly established that for each adobe soil the optimum amount of mixing water which gives the highest strength and density can be determined [15, 19]. Reasonably direct correlations between densities of dried adobe bricks and their compressive strengths have been obtained [14]. Schwalen [14] found the specimen size to affect the measured compressive strength. For example, reducing the size of test specimens from 6 x 6 x 3 inch prisms (15 x 15 x 7.5 cm) to 4 x 4 x 3 inch prisms (10 x 10 x 7.5 cm) resulted in an average reduction of 11 percent in the measured strength. Whittemore et al. [30] observed a more dramatic effect, the measured compressive strength was reduced by approximately 50 percent when the test specimen size was reduced from 11 11/16 x 15 1/4 x 4 15/16 inch (29.69 x 38.74 x 12.54 cm) to 11 9/16 x 7 7/16 x 4 15/16 inch (29.37 x 18.89 x 12.54 cm). These findings clearly indicate the need to establish a standard specimen size for measuring the compressive strength of adobe bricks.

The tensile strengths of adobe are comparatively low and difficult to measure accurately because of the effects of shrinkage cracks. Reported values range from 54 to 121 psi (0.37 to 0.834 MN/m^2) with the ratio between the compressive strength and tensile strength being about 6 [13]. Schwalen [14] found that the modulus of rupture for 10 different series of adobe bricks ranged from 29 to 88 psi (0.20 to .61 MN/m^2). In general, soils with high clay contents produce adobe brick with low flexural strengths [11].

This review indicates that the mechanical properties of adobe are not well-characterized. For example, little information on the creep and stress-strain relationships of either dry or wet adobe have been reported. Furthermore, the effects of moisture on the compressive and tensile strengths of aged adobe need to be determined before the structural soundness of historic adobe structures can be ascertained. Apparently nondestructive evaluation (NDE) techniques such as ultrasonic pulse velocity measurements and probe techniques [35-36], have not been employed to estimate the mechanical properties of adobe.

2.4 Concluding Remarks

The development of standard methods and tests to characterize the composition, microstructure, and the physical and mechanical properties of adobe materials is fundamental to the advancement of adobe preservation technology. The implementation of standard methods and tests will be of assistance to the National Park Service in the assimilation and interpretation of data from different sources. Furthermore, standard tests should form the basis for evaluating the effectiveness of preservation materials and methods.

Many of the important properties and features of adobe soils and building materials that should be characterized have been identified in this section. Methods which can be used for these and other characterizations should be identified and, if necessary, new methods developed.

3. Stabilized Adobe

Admixtures (stabilizing agents) can be added to the adobe soil and water mixture during the production of adobe building materials to increase the weathering resistance of the product (compressive strength may or may not be affected) [1]. Because stabilized adobe brick are sometimes used as a replacement for deteriorated adobe in the preservation of historic adobe structures, this class of materials is covered by this review.

The most commonly used stabilizers appear to be portland cement, lime, bituminous emulsions, and sand. A variety of other materials have been investigated or proposed as stabilizing agents and are briefly discussed in this section.

3.1 Portland Cement

Portland cement is an effective admixture for many adobe soils which improves both their strength and durability [1, 5, 6, 15, 19, 20, 30, 33, 37-41]. For example, a 12 percent addition, by weight, of portland cement to a "sandy soil" increased the compressive strength by a factor of 5 compared to the neat (unadulterated) soil [15]. Soil-cement adobes are more resistant to weathering, rain damage, and freeze-thaw damage than are the neat adobes [15, 19]. They shrink less during curing than the neat adobe. The thermal expansions of adobes are only slightly affected by low additions of portland cement [15].

Almost all soils can be stabilized with portland cement, however, soils with higher clay contents require higher percentages of cement to achieve the desired strength and durability [40]. Recommended proportions of cement to soil vary from 1 part cement to 8 to 20 parts of soil [33, 40, 41]. The optimum amount of mix water depends on the compositions of the soil and cement and the mix design [15]. Methods of preparing adobe soil-cement bricks are described in detail in references 1, 5, and 6.

A disadvantage of using adobe soil-cement materials for replacing deteriorated materials in historic structures is the difficulty in duplicating the color and texture of the original adobe. No doubt this problem arises with the use of most stabilizing agents.

3.2 Lime

Slaked lime (CaO) is used alone or in combination with portland cement to stabilize adobe. At least a 15 percent lime addition, by weight, is necessary to effectively stabilize adobe. However, this amount can be reduced to 10 percent by adding 5 percent (based on the weight of dry soil) portland cement [41].

The hydrated form of lime, calcium hydroxide ($Ca(OH)_2$) has been reported [13, 41] to substantially reduce the compressive and tensile strengths of adobe (table 1). Addition of calcium hydroxide has little effect on the weatherability of adobe [13].

3.3 Bituminous and Asphaltic Emulsion

Bituminous and asphaltic emulsions and similar types of materials have been used successfully for years to waterproof adobe [1, 19, 42]. The optimum amount of bituminous and asphaltic emulsions depends on the soil and four to eight percent, by weight, are commonly added [1]. Asphaltic emulsions are of two types, anionic and cationic. In anionic emulsions, the asphalt droplets are negatively charged by an alkaline water phase; whereas in the cationic emulsions, the asphalt droplets are positively charged by an acid water phase. The anionic emulsion should be used to stabilize positively charged soils, and the cationic emulsions should be used with negatively charged soils [42]. The method of preparing stabilized adobe with emulsions is described in reference [1].

Some bituminous and asphalt materials could, in some cases, impart an objectionable color to adobe brick if they are used for the preservation of some historic adobe structures.

3.4 Sand

Sand can often be added to soils with high clay contents to yield soils of adequate properties for adobe production [1, 6, 13, 19]. The addition of sand will reduce the early age strengths of the adobe but the long-term effect should be small [13]. The shrinkage cracking, water absorption, and weatherability of high clay soils will usually be improved by the additions of the proper amount of sand [19]. Worn and round sand, sometimes located in desert regions, has been found to be an unsatisfactory material for the dilution of high clay soils [23].

3.5 Other Stabilizing Agents

A variety of other stabilizing agents have been proposed which have generally received little or localized attention. It is difficult to judge the effectiveness of many of these agents on the basis of limited investigations and, therefore, they are only briefly covered.

Among the suggested stabilizing agents are blood and protein [43], vinyl acetate [44], sawdust [45], casein glue [42], vinsol resin [46], and aniline [42]. A series of materials were studied by Eyre [13] and others [14, 18, 19, 22, 42, 47] in the United States during the period of 1920 to 1950, and a qualitative assessment of the effectiveness of these materials is given in table 1. Eyre [13] did observe that the addition of 0.1 percent, by weight, of sodium carbonate increased with compressive strength of one adobe by 64 percent. It has been suggested that chemicals should be used to modify the pH of adobe soils [13] and to convert soluble salts to unsoluble salts [34]. However, a systematic investigation of the chemical treatment of adobe soils has not been performed.

Table 1. Stabilizing Effect on Adobe of Some Materials

Additive	Effect on Strength	Effect on Resistance to Water	Comments
Gypsum	slight decrease in compressive strength	slightly improved	Twenty percent addition resulted in a significant reduction in shrinkage.
Sodium Silicate	slight reduction in compressive and flexural strength	unchanged	No apparent improvement in properties of adobe.
Hydrated Lime	compressive and tensile strengths decreased by over 75 percent	slight reduction	Adobe paste was grainy, less plastic and less cohesive than untreated adobe.
Iron Chips	slightly increased the compressive strength but decreased the tensile strength	slight reduction	Three percent added to adobe mix.
Aluminum Sulfate	no effect	slight increase	0.1 percent added to adobe mix.
Soap	slight reduction in compressive strength	improved by over 25 percent	0.1 to 0.2 percent added.
Straw	little effect on compressive strength, some improvement in flexural strength	slight reduction	Reduces shrinkage cracking. In general, no benefit if used with good adobe soil.
Manure	20 percent reduction in compressive strength	no effect	According to Eyre [13], "use of manure is indefensible and only exists due to misguided custom."
Asphalt (Roof Coating Type)	not known	marginal improvement	
Road Oil and Reduced Crude Oil	not known	marginal improvement	

A type of material which is being considered for making durable adobe brick is made combining a soil with a polymer. Soil-polymer materials have been prepared by two processes: (1) monomer is added during the mixing of the soil with water and after the soil specimen is cured the monomer is polymerized by either gamma radiation or by the application of heat; (2) cured soil specimens are impregnated with monomer which is subsequently polymerized by gamma radiation or by the application of heat [48]. A wide range of compressive strengths (9 to 1300 psi (0.6 to 8.96 MN/m^2)) have been obtained depending on the method of preparation, moisture content of the soil, and the monomer-polymer system [48, 49]. It appears that further developmental work is necessary before these types of material can be used for preparing adobe brick.

3.6 Concluding Remarks

No doubt other materials not covered by this review have been used and some of them may even be effective in stabilizing adobe. It does appear that adequate stabilizing agents such as portland cement, lime, and emulsions are available and that other promising materials are being developed. Three important factors must be considered, however, in selecting stabilized adobe for replacing deteriorated materials: (1) extent of color and texture duplication between the stabilized and original adobe; (2) compatibility of the physical properties of the stabilized and original adobe; and (3) the potential damage to the original adobe caused by using a substitute which has higher mechanical properties and which is more durable. Usually the weakest component of a structure deteriorates the most rapidly and replacing it with a more durable material can accelerate the deterioration of the remainder of the structure. For example, replacing the adobe mortar joining together adobe block with an adobe-cement mortar has been found to often accelerate the deterioration of the adobe brick.

4. Preservation of Adobe Structures

The durability of adobe structures is largely dependent on factors encountered during their original construction including proper design, good construction practices, good soil selection, and the climate [42]. Unfortunately, these are factors over which the preservation scientist has no control. McHenery [50] has stated the problems well, "Restoration can be accomplished but it requires considerably more skill to 'restore' an old adobe than to build one from scratch." Preservation can be even more difficult than restoration, especially if the structure has no roof [10]. Systematic and effective preservation programs must be developed to overcome these obstacles to the preservation of historic adobe structures. The first step in developing an effective restoration program for historic adobe structures is to achieve an understanding of the major processes causing the deterioration of the adobe building materials. Effective preservation methods can then be selected.

4.1 Moisture in Adobe Structures

4.1.1 Deleterious Effects of Moisture

The deterioration of adobe and similar constructions have been largely attributed to shrinkage cracks, erosion, undercutting at the base, and loss of mechanical properties [42]. In most cases, these deterioration processes are directly or indirectly correlated with the presence of excess moisture. For example, most adobe walls will swell upon becoming damp and shrink upon drying, resulting in their cracking. If the wet and dry cycles continue over a period of years, the size of cracks and extent of cracking can become sufficient to endanger the structural integrity of the wall [42]. Rain water is the main cause of erosion and contributes, along with ground water, to undercutting of walls. The eroding effect of wind-blown sand on adobe has been often mentioned [12, 42], but documented evidence of such damage has not been uncovered in this review. Probably, water erosion is a more severe problem in most locations than wind-sand erosion. Excessive moisture in adobe walls, undoubtedly, can reduce the strength of the building material sufficiently to cause the collapse of the structure. Furthermore, excessive moisture combined with cycles of freezing temperatures can result in freeze-thaw damage [19].

In places where little or no rainfall occurs, adobe and similar structures have satisfactory durabilities [42]. This durability is evidenced by the longevity of the Zigguart of Agar Quf in Iran [12, 22], structures at Chan-Chan, Peru, and at Sian Fu, China [1, 22, 42]; all built of earth and believed to be over 2,000 years old. The long-term preservation of historic adobe structures, therefore, appears to largely depend on the success of keeping the structures dry. It is difficult, however, to keep adobe structures dry, even in the arid southwestern region of the United States where the rainfall may be 6 inches (15 cm) or less (the total annual rainfall may take place in one or two severe rainstorms, which is more harmful to adobe than a moderate rainfall [12]).

The traditional approach of protecting adobe walls, either free-standing or walls of structures, from water has been to coat them with some type of "waterproofing" material [1, 10, 12, 42]. These materials vary in type from a thin paint coating to a thick portland cement stucco [51]. This approach, however, addresses only one of three main processes by which water erodes, undercuts and, in general, weathers adobe structures. These processes [8], shown in figure 2, are:

(a) action of rain water on the top of walls resulting in the formation of deep fissures and cracks in the top and vertical surfaces of the walls,

(b) slow erosion of the vertical surfaces of walls,

(c) undercutting at the base of walls due to the action of salt-containing ground water or of accumulated rain water.

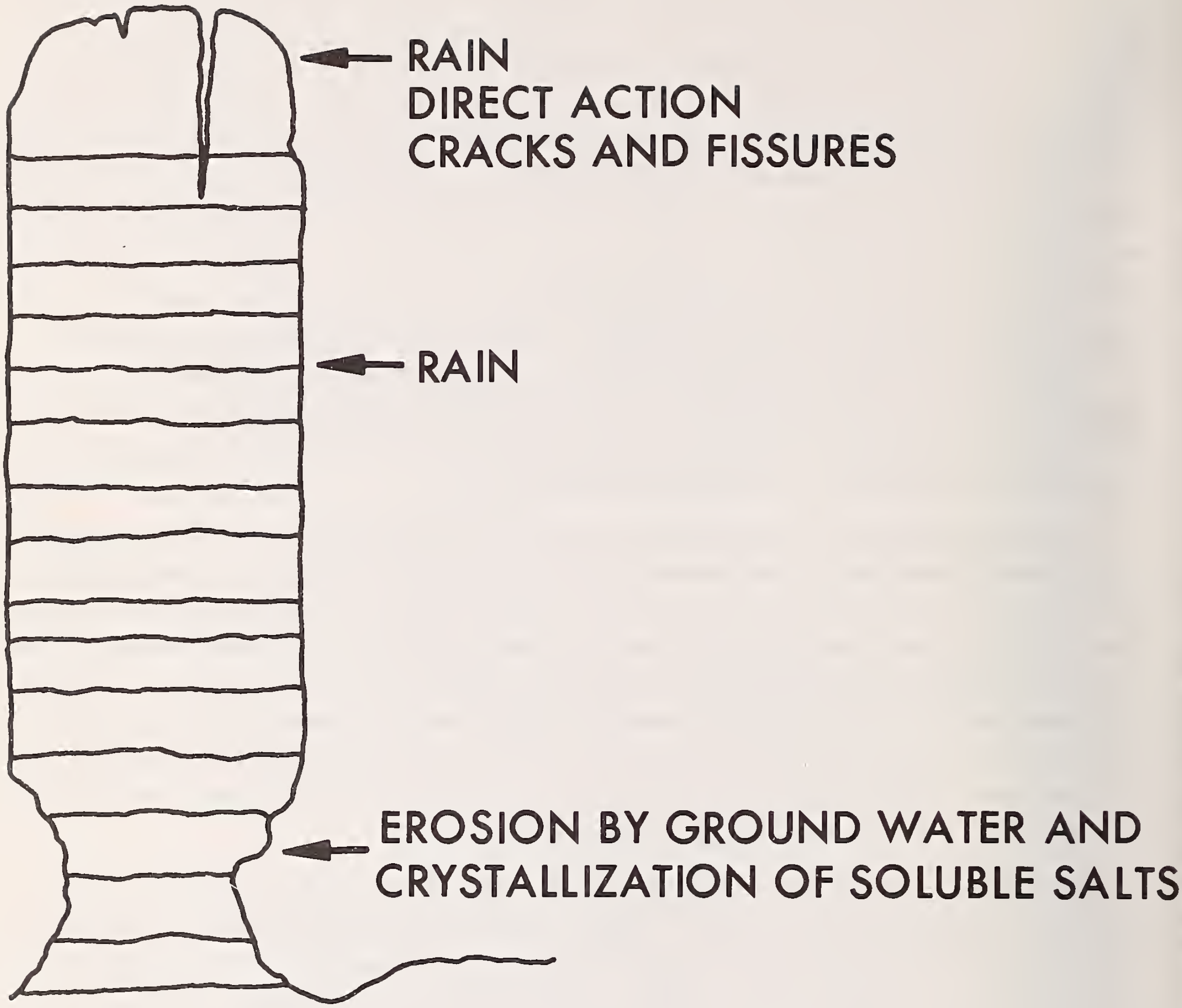

Figure 2. Deleterious Action of Water on Adobe Walls.

Torraca [8] and Steen [10] have concluded that processes (a) and (c) cause much more damage than process (b). Apparently, the vertical surfaces of adobe walls normally suffer little damage when exposed to the full force of driving rains [10]. Ground water (process c) can be especially harmful because most historic adobe structures do not have adequate waterproof foundations and water usually rises by capillary action up the wall to just above the ground surface and then evaporates. If the ground water has a high salt content, a salt efflorescence will be deposited just below the surface of the adobe wall as the water evaporates. This can result in a rapid undercutting of the wall [8, 10, 12, 52].

4.1.2 Mitigating the Effects of Moisture

Battle [53] has stated that "a good tight roof with ample and positive drainage will do more than anything to preserve an adobe structure." This approach will certainly assist in the mitigation of one of the most severe deleterious effects of water i.e., process (a). Unfortunately, many historic sites have either inadequate roofs or no roofs at all. Furthermore, often the decision is made to preserve ruins and roofless structures in their present state rather than restoring them [10]. However, if the structure has an existing roof or originally had a roof, the merits of repairing or reconstructing the original roof should be considered. Another approach is that taken to protect the Casa Grande ruins [10]; i.e., the construction of a separate high roof over the structure. The possibility that a high roof could cause the creation of damaging wind turbulences should be considered. If all of these approaches are unacceptable, then a routinely-scheduled maintenance program should be implemented [53]. The eroded adobe can be replaced with new adobe or with stabilized adobe. However, stabilized adobe must be used with caution, because as mentioned in Section 3.1.6, replacing the eroded adobe with a more durable material can accelerate the erosion of the remainder of the structure.

The deleterious effects of ground water and accumulated rain water on the base of adobe walls can be mitigated by providing drainage around the wall. Steen has suggested [10] digging trenches around adobe walls and filling them with gravel of sufficient size to prevent the rise of capillary water. Alternatively, the immediate soil can be "waterproofed" with a soil stabilizer [24] accompanied by the sloping of the adjacent ground away from the wall.

Either of two methods is usually selected to protect the vertical surfaces of adobe walls from slow erosion due to rain water or sand-laden wind; coating the vertical surfaces with surface coatings or surface impregnation materials [51, 52], or replacing eroded adobe with new adobe [10, 53]. Often, the surface coatings and surface impregnation materials have been ineffective and at times have accelerated the deterioration of the adobe [8, 10, 53] for reasons discussed in Section 4.3. Because of the slow erosion rate of vertical wall surfaces [13], the replacement of eroded adobe with new adobe is often sufficient to preserve the adobe structure [53].

4.1.3 Methods for Moisture Determinations

The determination of the source of moisture, amount of moisture, and water movement in adobe structures is an important aspect of their preservation. For example, coating the vertical surfaces of an adobe wall with a "waterproofing" material is a wasted effort when the source of the moisture is a leaky roof or ground water. Moisture determinations are also important when evaluating the effectiveness of a preservation process.

The only thorough measurements of source of moisture, moisture contents, and moisture flow in adobe structures uncovered during this literature review was that reported by Gullini and co-workers [12, 52]. The migration of water in structures located in Iran were monitored by taking electrical resistivity measurements. The types of and amounts of soluble salts in adobe building materials were determined from x-ray powder diffraction patterns of cored adobe specimens. (Briefly, the destructive effects of processes (a) and (c) (Section 4.1.1) were confirmed.)

A major problem associated with the use of electrical resistance meters (commonly called "moisture meters") is the lack of guidelines covering their use and the lack of standard calibration materials. Furthermore, the electrical resistance will be affected by the salt content of adobe. Kreigh and Sultan [24] have suggested the use of the neutron probe technique for moisture determinations in adobe structures and the surrounding soil. The use of the neutron probe is covered by ASTM Designation: D30.7 [54]. If properly calibrated, the neutron probe is a reliable method for measuring moisture of soils [17, 55-58]. To measure the moisture contents of adobe walls, relatively large-sized cores (1 to 2 inches (2.5 to 5.0 cm)) must be removed to accommodate the head of the neutron probe. An unacceptably large number of access holes would probably be required to obtain an adequate moisture profile of an adobe structure. Backscattering gamma devices are useful for measuring densities and thereby indirectly moisture contents of soils for depths up to 6 inches (15 cm) [17, 55, 56, 59]. The microwave technique has been used to estimate the moisture contents of soils [60, 61], but its applicability to adobe has not been ascertained. Other nondestructive methods to measure moisture contents of soils include: radar [62], thermal conductivity measurements [63], ultrasonic techniques [55, 58], and visible and infrared reflectance methods [64].

Drying soil specimens at 110°C to constant weight is the standard laboratory method of measuring moisture contents and is covered by ASTM Designation: D2216 [65]. This method is normally used to calibrate nondestructive methods for measuring the moisture contents of soils [58]. However, such a calibration is meaningful only if the chemical and physical properties of the soils selected for calibration purposes are well characterized, which suggests that standard reference materials for moisture calibration purposes should be established.

4.1.4 Removal of Moisture from Adobe Structures

Removal of excess moisture from adobe structures may be necessary if the strength of the adobe has been severely reduced to the level that the stability of the structure is impaired. Little work, apparently, has been carried out on methods for removing moisture from adobe structures except to protect a structure from rain and ground water and then allow it to dry gradually [52]. The methods covered in this section have been used for removing excess moisture from soils or for changing the direction of water flow in soils.

Electro-osmosis is an electrochemical method for stabilizing soils in which direct electrical current flows between electrodes buried in the soil in response to an applied potential difference of up to 100 volts [66-69]. The current is transmitted primarily by the movement of ions through the pore water of the soil; as the ions move, they carry with them some of the pore water. The water is generally transported in the direction of the cathode (negative electrode). The cathodes are usually perforated pipes to allow the water flowing toward the cathode to escape under its own flow or, more effectively, through a pumping system. Electro-osmosis treatment stabilizes soil through several processes [70] including: removal of water resulting in consolidation of the soil and improvement in strength; change in pH; alteration of clay materials; and modifications in water flow patterns. Electro-osmosis has been successfully used on a number of occasions to provide temporary stabilization of soils during excavation [66, 71].

The electro-osmosis method is most effective for soils having low clay contents and soils having high water contents [66, 69, 72, 73]. It is doubtful if this method can be used to reduce the water contents of soil to its optimum value because the efficiency of the process decreases rapidly after the removal of a small portion of the water [72]. The removal of just a small amount of water, however, is often sufficient to produce large strength gains [67]. Although only a small amount of water is removed, a large amount of water can accumulate at the cathode [72] and if not rapidly removed, can cause slumping and collapse of the soil in the vicinity of the cathode [73, 74].

Electrochemical hardening is a modification of the electro-osmosis process in which ions are electrolytically introduced into clay soils by using an aluminum anode immersed in an aqueous solution of aluminum chloride [74]. Magnesium ions [75] and calcium chloride [73] have also been electrolytically introduced into soils and other salts, acids and bases can be used [76]. Winterborn et al. [76] have noted that while electrochemical hardening is a promising method for soil stabilization, a good practical field approach has yet to be developed.

The moisture contents of soils can be reduced by exposure to elevated temperatures, which are often accompanied by improvements in the mechanical properties of the soils [76]. Thermal treatments in the range of approximately 450 to 900°C can have several beneficial effects on soils such as improving their water resistances, reducing their swelling capacities, and reducing their plasticity [77-78]. The temperature required to stabilize soils depend on their composition and the type of chemical bonding binding together the soil particles [78]. According to Winterborn [76], "an effective and economical field system of thermal stabilization has yet to be developed." The application of thermal treatment to an existing adobe structure must be carefully considered because induced thermal stresses could affect its structural integrity. Interestingly, merely prolonged exposure to sunlight can improve the compressive strength and water resistance of most adobe soils [79].

Before any of the methods reviewed in this section or any other proposed methods are used to remove moisture from adobe structures, further exploratory studies are necessary to determine their effectiveness. The effect of any de-watering process on the structural integrity of adobe structures must also be considered. For example, rapid water removal can possibly cause extensive cracking to take place in the adobe building material because of shrinkage or differential settling.

4.2 Resistance of Adobe Structures to Natural Hazards

Because of the low unit structural strength of adobe wall construction, adobe structures are often severely damaged during earthquakes and severe windstorms [13, 80]. Much of the poor resistance of adobe structures to earthquakes has been attributed to poor workmanship and poor design which resulted in structures having little resistance to lateral forces as imposed by earthquake shock [80]. To resist these forces an adobe structure should have a monolithic foundation combined with vertical and horizontal reinforcement with the walls well anchored together at the corners [1, 80, 81]. If possible, heavy roofing materials should be replaced with lightweight materials and the structural roof system should be stiff in its own plane and should be anchored to both side and end walls to serve as a diaphragm to more evenly distribute forces and distortions to the supporting walls [1].

Concrete footing walls have been placed along each side of old adobe walls to upgrade the foundation. These concrete footing walls are tied together with closely spaced steel tension bars that pass through the old adobe wall base. The new concrete is kept below grade to preserve the authentic appearance of the adobe structure [81]. It has been suggested [81] that, if possible, reinforced concrete beams should be installed at floor levels and at tops of walls to provide positive anchorage with the beams being concealed within the wall structure.

Kreigh and Sultan [24] have investigated the feasibility of reinforcing adobe structures by injecting liquid epoxy into vertical and horizontal holes drilled into the adobe walls. They formulated a slow curing, low viscosity epoxy which has been shown to penetrate the adobe and to fill pores, cracks, and fissures. The effectiveness of this approach in strengthening an actual structure has not been determined.

The use of steel reinforcing bars and steel wire mesh has been recommended [1, 80] for reinforcing adobe structures located in earthquake or high wind areas. Reinforcement should be provided around all openings in the adobe structure as well as at the corners [80]. Bamboo has also been used to reinforce adobe structures [80].

Before any method is selected to reinforce an adobe structure, the potential dangers of natural hazards should be evaluated. A methodology is presented in reference 82 to evaluate the amount of structural damage which could take place if a structure is exposed to the extreme natural environments encountered in earthquakes, hurricanes, and tornadoes.

4.3 Preservation Materials

A wide range of materials have been employed to protect adobe and earth structures. These can be roughly divided into four major categories: (1) stuccoes and plasters; (2) surface coatings; (3) surface impregnation materials; and (4) consolidation materials. The distinctions between these categories are made more apparent during the following discussion of the respective materials.

4.3.1 Stuccoes and Plasters

Cement stuccoes[7/] have been used extensively in attempting to protect vertical surfaces of adobe walls from rainfall [42]. This extensive use can probably be attributed to the availability and low cost of the constituents of stucco because, in many cases, stuccoes have not been effective in protecting adobe from water. This poor performance has been attributed to the lack of bond development between stuccoes and adobe as well as the tendency of stuccoes to crack [10, 52]. It has been frequently observed that moisture accumulates at the stucco-adobe interface, which accelerates the disintegration of the adobe [10]. These processes are similar to those through which unprotected adobe walls are eroded by water (figure 2) except that the stucco forms a barrier to the passage and evaporation of moisture and, therefore, the deleterious effects of water at the stucco-adobe interface are often not visually apparent until a portion of the wall collapses [10].

Various methods have been developed to upgrade the performance of stuccoes including: (1) applying stucco to wire mesh nailed to adobe walls [19]; (2) formulating stuccoes which are lean in cement e.g., stuccoes with mix proportions of cement:lime:sand in the range of 1:2:9 to 1:3:12 have been used [42]; (3) applying the stucco to dampened adobe surfaces [42]; and (4) the use of a primer coat prior to application of the stucco [1]. However, no evidence has been uncovered during the course of this review which documents the satisfactory performance on stucco over a period of years. Soil-cement mortars appear to be no more effective than stuccoes [10].

7/ An exterior finish for walls consisting of cement, sand, hydrated lime, and water [83].

Lime plasters have been applied successfully to adobe walls for many years [1]. These plasters are durable if they do not crack and if moisture does not accumulate at the plaster-adobe interface [1, 10].

Gypsum plasters have been used in a few arid regions, such as Cyprus, to protect earth walls [42]. However, gypsum is sufficiently soluble in water that gypsum plaster surfaces are susceptible to water erosion [84].

Dagga-mud plaster[8/] has been used over earth walls for many centuries in many parts of the world [1, 6]. In its unstabilized form, this plaster is probably no more durable than the adobe substrate but the plaster is easily prepared and readily applied to adobe and, therefore, can be incorporated in an effective maintenance program. Dagga-mud plasters have been stabilized with asphalt emulsions with good results [1, 42]. Because of the possiblity of a dark color, this type of stabilized plaster would not normally be useful in preserving historic adobe structures.

4.3.2 Surface Coatings

Surface coatings form thin films on the surfaces of adobe and earth walls providing temporary protection and also improving the appearance of the walls. Various types of surface coatings have been used, including: oil base, resin-base and emulsion paints [42, 51]; portland cement washes and white washes [1, 6, 42]; coatings of plant extracts [1, 85]; and coatings of fresh blood [43].

In a thorough study of the effectiveness of paints and plasters for rammed-earth walls, Patty [51] found that exterior lead-oil paints of good quality were the most satisfactory paints tested. This conclusion appears to be a controlling factor regardless of the type of paint or wash. Probably, the most significant finding of this study was that "contrary to expectations, the penetration of paints was undesirable. Paints and priming coats that penetrated the wall material caused deep failures on the surface and, in no case, did deep penetration of the material have any advantage." This negative effect of deep penetration of paints into adobe surfaces was later verified by Legavit [86]. The consequences of this finding are amplified in section 4.3.3 of this review which covers surface impregnating materials.

Typical primer coatings which have been applied to adobe walls to form a base for the topcoat paints are thinned aluminum paint [51], asphalt-based aluminum paint [18], linseed oil and glue sizing [1]. Legavit [86] reported that some of the difficulties associated with penetration of the paint could be mitigated by applying a primer coating consisting of the adobe soil mixed with a flour and water mixture.

Whitewash has often been applied to adobe walls to protect them from rainfall [1]. Whitewash normally consists of hydrated lime mixed with sufficient water so that it has a consistency similar to paint. Such a coating is inexpensive and easily applied but it is neither durable nor waterproof [5]. A more durable whitewash can be prepared by adding

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8/ Dagga-mud plaster is a mixture of clay and sand used as a plaster to protect adobe walls [1].

caesin, trisodium phosphate, and formaldehyde to the lime-water mixture [5]. A similar wash can be prepared by replacing the hydrated lime with portland cement [1]; although this substitution will be accompanied by a color change unless a white type of portland cement is selected. Washes should be applied to the substrate after it has been treated with a primer coat of the type used with paints.

Protective coatings for adobe walls have been obtained in Africa and South America by crushing the plant "Euphorbia Lacter," a common variety of the rubber plant family. A sticky liquid is obtained which is directly applied or mixed with slaked lime prior to application. Similar coatings are made in South Africa from the leaves of a cactus of the Optuntin family and from agave leaves [1, 85]. The extracts from these types of plants are usually toxic and, therefore, these liquids must be used with caution [1, 85].

Coatings of fresh blood have been found to increase the water resistance of adobe surfaces [43]. Apparently, monolayers of blood proteins are adsorbed on the clay particles thereby temporarily improving the water repellance of the adobe. Proteins from gelatin [87] and egg albumen [88] have also been found to be strongly adsorbed on clay particles.

Surface coatings do not form durable waterproof films on adobe and earth walls [1, 42]. For example, Patty [51] has convincingly shown that moisture can pass in and out through paints and similar coatings applied to earth walls. These materials form thin films which are vulnerable to scratches and abrasion. Furthermore, flaking, peeling, blistering, and crazing also reduce the protective capabilities of these coatings. Often, the occurrence of flaking and peeling is evidence of the presence of moisture at the coating-substrate interface [42]. Even with these deficiencies, surface coatings can be effective in a preservation program stressing continued maintenance. These coatings are usually inexpensive, easily applied, and probably will not cause any irreversible harm to the adobe surface.

4.3.3 Surface Impregnation Materials

Surface impregnation materials are materials that penetrate the surface layers of adobe or earth walls to a finite depth and both "waterproofs" and consolidates these layers. Often they are organic-silicates or organic monomers which are polymerized in-situ or are prepolymerized and dissolved in a solvent prior to application. Examples of polymer systems that have been applied to adobe walls are polyurethane [10], members of the acrylate family [8, 81], ethyl silicate [8, 12, 52], and silicones [52].

Only limited success has been achieved with surface impregnation materials. Similar to the case of paints, impregnation of the adobe surface has had a negative effect on its durability [8, 10, 53]. Discontinuity of properties exist between the impregnated and unimpregnated regions and stresses at these interfaces, caused by differential thermal expansion or by structural loads, can result in cracking. Moisture can then enter and accumulate at the boundary causing the weakening of the interfacial bond. Freeze-thaw damage can also occur culminating in the complete disbonding of the treated region. Concerning surface impregnation of adobe walls, Torraca [8] has stated, "as far as penetration is concerned, unless one can penetrate the whole wall and produce a homogeneous material

material, the less penetration the better." Battle [53] and Steen [10] have reported that while the application of a polyurethane to adobe walls gave excellent results for the first few years, that its use ultimately resulted in the destruction of significantly larger amounts of adobe than if the walls were not treated.

Clearly, surface impregnation materials should be used with caution and their effectiveness evaluated by appropriate research prior to their application to important adobe structures. The effects caused by these materials are essentially irreversible i.e., their removal would be extremely difficult without severely damaging the treated regions.

4.3.4 Consolidation Materials

Consolidation materials are those materials which can be intruded into the mass of adobe and earth structures to fill pores, voids, and cracks in the soil matrix, thereby, enhancing their structural integrities and also "waterproofing" them. No reports were uncovered in this review of the actual intrusion of consolidation materials into the fabric of adobe or earth structures. Some materials which may serve as consolidation materials are: surface impregnation materials (section 4.4.3); low viscosity epoxies [24]; and a variety of soil stabilizers such as organic resins [76, 89-91], silicates [91-92], and petrochemical liquids [93]. Concerning soil stabilizers, Kinton [91] reported, based on a very comprehensive study lasting over 20 years in which nearly all types of materials were considered, that "no single chemical or combination of chemicals have been found acceptably effective or economical as a major soil stabilizer." However, he noted that current and planned research may possibly lead to the development of chemical treatments which are effective in controlling volume changes in soils, improving moisture-density relationships, and reducing frost action, etc. The review by Mura and Thornburn [94] on stabilization of soils with inorganic salts and bases, also stressed the need for further research. They concluded that the type and exact percentage of chemicals most beneficial to strength are unique for each soil and depend upon the physical, chemical, and mineralogical composition of each soil. This conclusion certainly should be applicable to adobe soils and to salts used in electrochemical hardening methods (section 4.1.4).

No doubt, that with the rapid advancement in the synthetic polymer field, the use of polymeric materials to consolidate adobe structures will be contemplated. Warner [95] has cautioned engineers in the indiscriminate use of polymers to solidify soils. For example, polymeric materials often deform and creep under stress so that the fundamental strength (the load at which no load relaxation takes place) of solidified soils may be as low as 20 percent of the ultimate strength (obtained from rapid loading) [95].

4.3.5 Concluding Remarks

Obviously, no unique material has yet been identified which will protect adobe walls from all the deleterious effects of water and other natural hazards. Until the effectiveness of a preservation material has been demonstrated in well-designed experiments simulating field conditions, it should be used with extreme caution. The damage caused by the indiscriminate application of preservation materials has often exceeded the effects of natural weathering [10, 53].

5. Summary and Conclusions

The successful preservation of most historic adobe structures depends largely on effectively protecting the structures from natural hazards, especially water. The initial phase of preserving adobe structures should consist of determining the processes leading to the deterioration, the extent of deterioration, and if water is involved, its source. Only after this phase is completed should preservation methods and materials be selected. In most cases, keeping the adobe building material dry will greatly contribute to the longevity of the structure. The selection of preservation materials and methods for an adobe structure should be based on well-designed laboratory and field investigations in which the experimental conditions closely simulate the actual exposure conditions. Existence of an universal preservation material or process is doubtful because many factors such as the properties of the adobe soil, deterioration processes and extent of deterioration, sources of moisture, etc., will vary to some extent from structure to structure. Therefore, the preservation of each adobe structure should be considered as an unique problem. After a preservation process is implemented or a material is applied, its effectiveness should be monitored over a period of years and the results thoroughly documented. This review disclosed only a few reports in which the long-term results of preservation practices were given.

An obvious need exists for the development and establishment of standard test methods to characterize the important physicochemical and mechanical properties of adobe soils and adobe building materials. Many of these important properties have been identified in this review. Standard test methods can be of great assistance in the assimilation and interpretation of test results obtained at different laboratories.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The physicochemical and mechanical properties of adobe soils and building materials, and the technology of preserving historic adobe structures have been critically reviewed. In most cases, the deterioration of adobe structures can be directly or indirectly correlated with the presence of excess moisture. Therefore, the successful preservation of most historic adobe structures depends largely on effectively protecting these structures from water. This review indicates that the technology of preserving adobe structures needs further development to ensure the longevity of the structures.

Areas in which research is needed have been identified and include: (1) the development of standard methods to characterize the composition and physical properties of adobe soils, and the mechanical properties of adobe brick; (2) nondestructive methods to measure the water contents of and watermovement in adobe structures; and (3) the evaluation of the effectiveness of different types of preservation materials and methods.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Adobe building materials; adobe soil; mechanical properties; moisture determination; preservation technology.

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