

THE EFFECTS OF SOLUBLE SALTS AND WETTING AND DRYING  
CYCLES ON THE COMPRESSIVE STRENGTH AND  
STABILITY OF ADOBE

by

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## ABSTRACT

The effects of wetting and drying cycles and soluble salt accumulations on the stability and strength of adobe material similar to that of Tumacacori Mission, Arizona, were examined. Cores of a selected soil were exposed to wetting and drying cycles with deionized water and solutions of the chlorides and sulfates of Ca, Mg, K, and Na. Cores were prepared by saturation of the CEC with either Ca, Mg, K, or Na. Stability was evaluated visually. Strength was tested by measuring the unconfined compressive strength of the cores.

Potential for surface deterioration of adobe walls exists in (1) wetting and drying cycles; (2) substitution of Ca and Mg on the CEC by Na and K; (3) adsorption of hygroscopic and/or hydrated moisture under conditions of high humidity, especially the chlorides; (4) retention of moisture under normal conditions by  $MgCl_2$  and  $CaCl_2$ ; and (5) hydration pressures of  $Na_2SO_4$  and  $CaCl_2$ . Practically, deterioration will be confined to surface or near-surface material. Crystallization pressures are a minimal problem.

Possible segregation of salts and accumulation limits in adobe wall interiors is discussed, with implications for production of superior adobe material.

## INTRODUCTION

The mission of San José de Tumacacori was built in the late eighteenth century by Franciscan priests sent by Spain to proselytize the Indians of the Pimería Alta on the frontier of New Spain. It is located in the fertile Santa Cruz Valley between Tucson and Nogales, Arizona, close to U. S. Highway 19 some 30 km north of the Mexican border. It is set on a low terrace elevated several meters above the Santa Cruz floodplain to the east. The highly variable rain rainfall averages about 75 cm per year, the majority of which falls in late summer thunderstorms.

In 1848 the mission was abandoned and fell into disrepair. It received Federal protection in 1908, and in 1921 limited repair work was initiated. The current policy of the National Park Service, which administers Tumacacori as a National Monument, is to preserve it in its present state of historic ruin (Jackson 1973).

The most serious problem affecting the stability of Tumacacori is the influx of subsurface moisture into the lower portions of the structure, since the foundations of the adobe walls are not sealed (Percious and Norvelle 1978). It is generally agreed that moisture causes adobe to deteriorate (Clifton and Davis 1977; Brown, Robbins, and Clifton 1978). Furthermore, salt accumulation left by

evaporating groundwater ultimately leads to severe disruption of the adobe matrix either through crystal growth, as in the case with gypsum, or due to their deliquescence, as is the case with calcium or magnesium chlorides, or both. Both effects occur in certain portions of Tumacacori and appear to be the major cause of deterioration of portions of the interior nave wall (Brown et al. 1978).

The purpose of this thesis is to examine the theoretical aspects of the effects of water and salts on the integrity of adobe, and then to devise and execute experimental procedures to test the effects of certain common soluble salts and wetting and drying cycles on adobe material similar to that at Tumacacori.

## LITERATURE REVIEW

Adobe is commonly a mixture of sand, silt, clay, and gravel; and often straw or other binding material, that is prepared for use as mud bricks, mortar, or in walls cast in place (Clifton 1978).

### Soil Fabric and Structure

An acquaintance with the principles of soil fabric and structure as they apply to engineering uses of soil is necessary to understand better the nature and properties of adobe, as is apparent from this definition by Yong and Sheeran (1973, p. 176):

The structure of soil has been defined as that property of soil which provides for its integrity. An important component of structure is its fabric, i.e., the physical arrangement of soil particles including particle spacing and pore size distribution. When soil fabric is considered in conjunction with bonding forces and particle interaction mechanisms developed, the structure of soil is obtained . . . and it is this structure of soil that responds to external and internal excitation and provides the characteristics of behavior observed in soil performance and testing.

Brewer (1964) divides the mineral constituents of soil into two groups, the skeleton grains and the plasma (also referred to as the matrix). The skeleton grains are larger than colloidal size (5 micrometers in this study) and are in the sand and silt particle size ranges. They are resistant to deformation, translocation, concentration,

and reorganization, but lend little or no cohesiveness to the soil mass. The plasma--clay, fine silt, and soluble matter--is composed of particles smaller than five micrometers. Although the plasma may be deformed, translocated, concentrated, and reorganized by various physicochemical processes, it provides cohesion to the fabric and is therefore of primary interest in this study.

The remaining volume of the mineral soil mass is composed of voids, or pore space, which conduct fluids and offer no resistance to deformation or rearrangement.

#### Factors Affecting Original Fabric Arrangement, Strength and Stability

##### Clay Mineralogy

Three major clay types were identified by X-ray diffraction analysis in the Tumacacori adobes: mica, montmorillonite, and kaolinite. These clays differ markedly in their physicochemical properties. All are phyllosilicates--crystalline substances containing in their simplest forms various two-dimensional arrangements of silicon-oxygen tetrahedra and aluminum- or magnesium-oxygen-hydroxyl octahedra (van Olphen 1977). The subject of clay mineralogy is much too complex to discuss in detail here, but it is important to consider the properties of these clays which most affect soil fabric. Unless otherwise indicated, the following characterizations are taken from van Olphen (1977).

Montmorillonite is a 2:1 phyllosilicate. Its unit cell consists of an octahedral layer sandwiched between two tetrahedral layers. Substitution for aluminum and silica by cations of lower valence results in a net negative charge that is compensated for by adsorption of exchangeable cations on the surfaces of the unit cells. Attractive forces between the unit cells are not sufficient to prevent entry of polar molecules, such as water and glycerol. Hence, when wetted, montmorillonite can swell to many times its dry volume. It exhibits the greatest colloidal properties of the three clays in Tumacacori adobes, including surface area, cation exchange capacity, and cohesiveness. Its fabric often consists of thin, crinkled and folded sheets which form a continuous, polymer-like network (Borst and Keller 1969). Montmorillonite's cohesiveness is an asset to adobe strength; its high shrink-swell potential is a liability to adobe stability.

Kaolinite is a 1:1 phyllosilicate. Its basic unit cell consists of one tetrahedral sheet and one octahedral sheet. Attractive forces between unit cells are strong enough to prevent entry of polar molecules. Since kaolinite often is arranged in thick, non-expanding stacks and since substitution of lower valence cations in the crystal lattice is limited, its effective surface area, cation-exchange capacity, and cohesive strength are low. In terms of properties of adobe, kaolinite is desirable because its low

shrink-swell potential reduces cracking. However, it has the lowest cohesive strength of the three clays.

Mica is a 2:1 non-swelling clay mineral. Interlayer potassium cations form strong enough bonds to prevent expansion. Its irregularly shaped plates and packets of plates are often haphazardly arranged, although book-like aggregates (Pusch 1973) and limited orientation also occur (Borst and Keller 1969). Mica's intermediate colloidal properties give it both strong and stable adobe forming properties.

#### Solution Environment

During the drying process and the formation of soil fabric, the kinds and concentrations of soluble salts in the soil solution affect the orientation of clay particles (Kazi and Moum 1973) and their closeness of approach (Vershinin 1971). These phenomena are manifestations of the double-layer theory, which is summarized below from van Olphen (1977).

Most clays possess a net negative charge. They differ greatly in their intensity of charge, however, according to the amount and location of isomorphic substitutions of cations. In a solution environment soluble salts are present as positively charged cations and negatively charged anions. In a solution containing clay, these ions are not distributed randomly, but rather the cations tend to be concentrated in the vicinity of the clay particles and

the negatively charged anions tend to be repulsed by the like charge of the clay. Likewise, the clay particles repulse each other. The swarm of cations around the clay, however, reduces this clay-to-clay repulsion, especially those cations nearest the clay surface.

The cations closest to the clay particles form the Stern layer, which is roughly defined as the depth of those cations which are adsorbed strongly enough to remain with the clay particle when it is moved. Outside the Stern layer is the diffuse layer, which is affected by the charge of the clay particle and so exhibits a greater concentration of cations close to the clay and a larger concentration of anions further away from it. Increasing the salt concentration of the solution compresses both layers and increases the concentration of cations close to the clay, further decreasing repulsion between clay platelets.

Because of varying charges and degrees of hydration of cations, different salts do not affect the clay-solution system equally, and therefore do not necessarily produce the same fabrics. For example, Pusch (1973) states that for montmorillonite the type of adsorbed cation seems to govern the fabric. Kazi and Moum (1973) report that the fabric of natural sediments is affected by the salt content of the water in which they are deposited. A higher salt concentration produces an open, cardhouse-like fabric with predominantly edge-to-edge and edge-to-face contacts between the

platelets. A lower salt concentration produces a dispersed system with more face-to-face contacts and a higher density.

Sides and Barden (1971) report that the fabric formation of mica clays was sensitive to the salt concentration but that the fabric of kaolinite was little affected.

Talme (1968) found that the type of adsorbed cation affects the physical behavior of soil. For example, he reports a reduction in shear strength of a sensitive clay when calcium and magnesium concentrations were reduced in relation to sodium and potassium. Vershinin (1971), though, indicates that the tensile strength of a podzolic loamy soil was greater for sodium- and potassium-saturated systems than for a calcium-saturated soil. These results are not necessarily contradictory since they were obtained from different soils at different moisture contents.

The significance of these phenomena to this study is that the interaction of different salt solutions and clays produce different fabrics and therefore do not exhibit the same physical characteristics.

#### Cohesion in the Soil Mass

The previous sections dealt with the factors that affect the arrangement of soil particles. Here the nature of the cohesive forces in soils is examined. Crawford (1963) asserts that the cohesion of a soil mass may be visualized as a frictional resistance mobilized by the

arrangement of, and the intrinsic stresses between, individual soil particles.

Simple friction between particles is an important factor in the resistance of the soil to deformation. The total percentage of skeleton grains is especially important since they are not deformable under normal conditions. In general, good strength in adobe is achieved by that ratio of skeleton grains and matrix which allows the skeleton grains to touch but which still contains sufficient plasma for good cohesion. Clifton and Davis (1977) consider that durable adobe contains 20-30% combined silt and clay.

Many observers, including Vershinin (1971), report that the cohesion of the soil mass decreases rapidly with increasing moisture content. When comparing a certain sierozem with a zero moisture content with the same soil at a 0.81% moisture content, he found an average decrease in compressive strength of 37%. At least part of this decrease is thought to be due to the lubricating effect of the water. Also, Ingles (1964) suggests that materials (such as salts) that crystallize upon drying may impart greater strength, apart from any cementing effect, simply by precipitating around particle junctions and increasing the frictional surface there. Water, therefore, by dissolving these wedges, can further decrease adobe strength.

There is considerable speculation about the role of cementation in soil cohesion. Crawford (1963) refers

vaguely to a "natural cementation" that increases in strength over time. Clifton and Davis (1977) compared the compressive strengths of adobe samples cured for 7 days with samples cured for 28 days and found an average increase in strength of 29% with the longer curing time. This effect could be the result of the curing of cementing material similar to the curing of concrete. However, Rosenqvist (1963) points out that there are other possible explanations, including slow formation of rigid bonds of structured water.

Vershinin (1971) notes that a thin layer of cement is actually stronger than a thick one, providing that surface irregularities are filled. He proposes that the weathered surfaces of the mineral grains are coated with a thin, amorphous film of substances such as iron and aluminum hydroxides, silicic acid, humic acid, and other substances that cement soil grains on drying.

Whatever the processes that may be involved, the important point to this study is that curing time affects the strength of the soil.

Electro static forces also play a role in soil cohesion. Some of the specific mechanisms proposed include van der Waals attraction (van Olphen 1977), coulombic forces (Quirk 1964), and capillarity (Ingles 1964). There is general agreement that these forces are very short-ranged (van Olphen 1977, Vershinin 1971). The type of

adsorbed cation, the solution concentration, and the clay type all influence the ability of clay particles to approach one another, and therefore influence the strength of the soil fabric formed. Also, by governing the geometry of the fabric, these same factors control the amount of surface area of the clay platelets that that is in close proximity.

#### The Effects of Water and Salts on Adobe Fabric

The composition and concentration of the soil solution can have great effects on the formation and the resultant strength and stability of adobe fabric. Since at Tumacacori many of the adobes have been subjected to changing solution environments, it is pertinent to examine possible effects of such changes.

#### Wetting and Drying Cycles

For agricultural purposes a crumb or granular soil structure is desirable, and the mechanisms of transforming a so-called "structureless" soil into a loosely bound network of peds has been extensively studied. There is general agreement (Vershinin 1971; Baver, Gardner, and Gardner 1972) that wetting and drying cycles aid this process, principally because of differential shrink-swell in the soil mass. Since shrink-swell is related directly to the amount of clay and its mineralogy, clay type, and particle size distribution

are important to the stability of adobe subjected to wetting and drying cycles.

#### Patternization of Salt Deposits

Krauskopf (1967) indicates some of the complexities that affect the precipitation patterns resulting from evaporation of a solution containing only two salts. The relative solubilities and concentrations of the salts, whether or not they have a common ion, and the temperature all influence the nature of the precipitation process. Often complexes precipitate rather than pure salts.

The presence of a soil medium vastly complicates an already complex situation. Clay and organic matter both adsorb and complex ions. Cations especially are affected by the predominantly negatively charged soil system. Yaalon (1965) experimented with the movement of chlorides and sulfates of a Sandy Hamra soil from Israel. He found that the flow of chlorides was little affected, but that sulfate ions were retarded. Thus, some anions also interact with the soil medium.

On a larger scale, geographic differentiation of soluble salts is common. Gale (1951) reported that in the Bristol Basin of California the location of various salt deposits depended principally on their relative solubilities. When shallow lakes in the basin dried, the relatively insoluble gypsum precipitated first. The final liquor

contained large concentrations of NaCl, and of CaCl<sub>2</sub>, which precipitated last.

Bazilevich (1970) reaches similar conclusions, but also reports concentrations of magnesium chloride in the residual liquor. He lists eleven separate steps in the overall precipitation pattern, including dissolution and reprecipitation of previously formed salts. In addition, he mentions at least eleven environmental factors that influence the process.

#### Fabric Changes

A change in solution environment may produce a change in soil fabric. A well-researched example is that of the so-called "quick" or "sensitive" clays, which are capable of suddenly losing their physical coherence to produce landslides and foundational instability. It is generally agreed that one of the major causes of this phenomenon is a change in fabric caused by leaching of the original pore water after emergence of a land mass from a saline depositional environment (Rosenqvist 1963, Pusch 1973). Rosenqvist (1963) found that micaceous clays display the properties of quick clays upon leaching, but that montmorillonitic clays do not.

Ravina (1973) observed that the clay particles of a Mizra soil from Israel were generally in the form of flat platelets when the cation exchanges sites were saturated

with Ca, but that K-saturated platelets were distinctly curled. Also, the general physical characteristics of the two systems were different. Borst and Keller (1969) refer to a Ca-saturated vermiculite with curled edges that tightened into scrolls or tubes after being saturated with Na. Thus, a change in solution environment may not only affect the orientation of clay particles, but also their shapes.

### Salt Crystallization

Evans (1969-1970) has written an excellent review on salt crystallization and rock weathering. He states that common soluble salts are capable of developing crystallization pressures sufficient to overcome the tensile strength of rock. One important reason is the crystals' propensity to grow directly against confining pressures because of a super-saturation effect achieved in the area of stress. The strength of adobe is clearly less than that of rock, so pressures sufficient to overcome the tensile strength of dry adobe should be easily attained.

### Hydration and Hygroscopicity

Hydration is a reaction of a substance with water in which the water molecule remains whole (as opposed to hydrolysis, in which the H-OH bond is split). The reaction is especially common with salts. Hydrates of definite composition are formed; i.e.,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ,  $\text{Na}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$ ,

and  $\text{Na}_2\text{SO}_4 \cdot \text{H}_2\text{O}$  (Clark and Hawley 1966). Of the chlorides and sulfates of Ca, Mg, Na, and K, the CRC Handbook of Chemistry and Physics (Weast 1977-1978) lists hydrated forms of all but NaCl,  $\text{K}_2\text{SO}_4$ , and KCl.

Winkler and Wilhelm (1970) note that the hydration status of a particular salt depends on temperature and humidity. Low temperature and high humidity favor the more highly hydrated forms. Changes in the temperature and/or humidity often result in a change in the salt's hydration status and consequently in its volume. Considerable pressures may be developed. For example, at 20°C and 100% RH the hydration of  $\text{Na}_2\text{SO}_4$  to  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  produces a theoretical pressure of almost 500 atmospheres. Winkler (1975) feels that common soluble salts in stone can develop sufficient hydration pressures to cause deterioration, especially since some salts can go through several hydration cycles in a single day.

The term hydration is also used to describe the reaction occurring at the surface of a mineral soil particle. When exposed to moisture, either liquid or vapor, clay surfaces and the cations adsorbed thereon adsorb water molecules in an orderly, stepwise fashion. Montmorillonite may double in volume simply by the addition of four monolayers of water from the atmosphere (van Olphen 1977). The energy of this primary hydration is too great to be

influenced under normal conditions except by changing the adsorbed cation (Quirk 1964).

Hygroscopicity is the property of a substance to adsorb moisture from the atmosphere. Many common substances, such as  $\text{CaCl}_2$ ,  $\text{MgCl}_2$ , and paper exhibit this property. Hygroscopicity differs from hydration in that it is a non-stoichiometric surface phenomenon (Hawley 1977). Some substances, such as  $\text{CaCl}_2$  and  $\text{MgCl}_2$ , become liquid in the process of adsorbing moisture. This special case of hygroscopicity is termed deliquescence (Clark and Hawley 1966).

In a soil-water-salt system it is in reality very difficult if not impossible to determine the exact status of the moisture therein.

## MATERIALS AND METHODS

Materials and laboratory procedures were selected to duplicate as closely as possible the interaction of soil, water, and salts in the affected portions of the walls of Tumacacori Mission.

### The Test Soil

#### Clay Mineralogy

X-ray diffraction analyses were run on 35 samples of clay extracted from original adobes representing all portions of the mission, including exterior and interior, and salt- and moisture-affected and unaffected areas. The clay fraction was first separated by the hydrometer method (American Association of State Highway Officials [AASHO] 1955) and a thin layer of clay paste spread on a ceramic plate. After air drying, the samples were successively treated with  $MgCl_2$ , glycerol, KCl, and  $550^\circ C$  and X-rayed after each treatment to determine the presence of montmorillonite, mica, vermiculite, kaolinite, and chlorite. Little variation was observed in the X-ray diffraction patterns. Montmorillonite and mica were found to be co-dominant, with moderate amounts of kaolinite also present.

After testing various commercial soil sources, a soil, referred to hereafter as the "test soil," was located that very closely duplicated the clay minerology of the Tumacacori adobes. The test soil was excavated from the B horizon of a soil that closely resembles the Continental series. It is located some 100 m inside the western boundary of property owned by the Tanner Companies, Tucson Rock and Sand Division. The test soil lies a few meters north of Escalante Road about 0.7 km east of the intersection of Escalante and Camino Seco Roads in Tucson, Arizona. This soil was used in all subsequent testing.

#### Particle Size Distribution

The particle size distribution parameters of the American Association of State Highway Officials (AASHO 1955) were used to characterize the soil materials in this experiment with one modification. Particles larger than 2 mm (gravel) were screened from all samples to achieve greater uniformity in testing, so percentages of sand, silt, and clay do not reflect any gravel that was originally present. Silt and clay contents were determined by the hydrometer method; sand was fractionalized by sieving (AASHO 1955).

Table 1 shows how the test soil was adjusted by the addition of washed mortar sand to approximate the particle

Table 1. Particle Size Analyses of Tumacacori Adobes and Original and Sand-Amended Test Soil

Particle Size Name <sup>a</sup>	Diameter	Average of Tumacacori Samples <sup>b</sup>	Range of Tumacacori Samples	Test Soil	Sand-Amended Test Soil <sup>c</sup>
	mm	-----%			
Clay	0-.005	14	7-25	24	11
Silt	.005-.075	35	18-45	29	13
Fine Sand	.075-.425	31	23-46	28	38
Coarse Sand	.425-2.00	20	12-28	19	38

<sup>a</sup>American Association of State Highway Officials (AASHO 1955).

<sup>b</sup>Twelve samples.

<sup>c</sup>Clean mortar sand: fine sand 46%, coarse sand 54%.

size distribution of Tumacacori adobes. Ideally, the addition of less sand would have given a closer match, but a 1.2 to 1.0 ratio of sand to soil was found to be the minimum necessary to prevent excessive cracking of the samples on drying.

#### Adsorbed Cation

Since the adsorbed cation on clay plays an important role in the geometry of the fabric formed and sometimes influences the shape of the clay particle, the test soil and a Tumacacori adobe sample unaffected by groundwater were analyzed for exchangeable cations (Table 2).

Table 2. Exchangeable Cations of Tumacacori Adobe and Test Soil<sup>a</sup>

Cation	Tumacacori Adobe	Test Soil
	-----% of CEC satisfied-----	
Sodium	1.1	0.5
Potassium	20.3	3.8
Calcium	60.2	88.1
Magnesium	18.3	7.8

<sup>a</sup>Analyzed by The University of Arizona, Dept. of Soils, Water, and Engineering, Soils Water and Plant Tissue Testing Lab. Method: Ammonium acetate (pH 7) replacement.

The soils do not match perfectly--the Tumacacori adobe has more K and Mg and less Ca--but Ca is clearly the dominant cation on the cation exchange capacities of both soils.

#### Preparation of Adobe Test Cylinders

An imaginary in situ core of adobe can transfer fluids in all directions, although typically the potential for transfer is not equal in every direction. To approximate as closely as possible natural conditions, the adobe containment device should therefore be porous. In addition, it should be inexpensive, uniform, allow easy extraction of the sample, and retain sufficient wet strength to contain the sample and infiltrating salt solutions without distortion. Good-quality cardboard mailing cylinders were found to meet these criteria. Cylinders with a 5.08 cm (2 in) inside diameter were used.

The cylinders were cut into 21.69 cm lengths and were inked on the inside with a band covering the area between 15.24 cm and 14.48 cm from the bottom of the cylinder. This band represents 5% of the total 15.24 cm of the cylinders to be packed with the sand-amended test soil. By packing all the cylinders so that the final volume fell within this band, densities of the adobe cores were maintained within a maximum range of 5% for consistency in testing.

The top 7.6 cm and the bottom 1.3 cm of the cylinders were waterproofed by dipping them twice in an acrylic resin emulsion, Rhoplex E-330, manufactured by the Rohm and Haas Company of Commerce, California. This was done to prevent unraveling of the cardboard spirals and to protect the top cavity (only 70% of the cylinders were filled with adobe) from the effects of containing infiltrating salt solutions.

Test mixtures were prepared to determine the ratio of amended test soil and water that produced a workable adobe material. The standard adobe batch used consisted of 1814 g of oven dried (105°C) test soil, 2177 g of oven dried washed mortar sand, and 500 ml of deionized water. Water content on a dry-weight basis was 12.5%. The batches were mixed for two minutes in a 4-liter Hobart electric mixer equipped with a planetary drive.

After mixing, 682 g of the wet adobe mixture was packed into the prepared cylinders so that the final volume fell within the inked band on the inside.

Initially, about 1/3 of the sample weight was placed into the cylinder, which was firmly held onto a paper towel lying on a smooth table top. To break up air pockets a cake knife was pushed into the mass about twelve times. The cuts radiated from the center to the inside wall of the cylinder. The mass was then firmly tamped with a length of dowel. Cutting and tamping were repeated. The

remainder of the mixture was added in like increments following the same procedure.

The samples were cured slowly at room temperature (about 23°C) and humidity (40-45% RH) for 48 hours to minimize cracking. Evaporation from the sample bottoms was prevented since they remained on the paper towel. Evaporation from the top was limited by loosely covering the cylinder.

The samples remained damp for a long period under room conditions. To accelerate the evaporation process and still remain within temperatures encountered in nature, the samples were dried at 43°C in a ventilated oven for 48 hours following the initial 48 hours of curing. Mesh shelves in the oven allowed evaporation from all surfaces. Finally, the samples were cured for at least 14 days at room temperature and humidity before treatment with salt solutions.

#### Treatment with Salt Solutions and Wetting and Drying Cycles

Brown et al. (1978) reported finding chlorides and sulfates of K, Mg, Ca, and Na in Tumacacori adobes affected by groundwater. These salts were used in this experiment. Cylinders were treated by infiltrating solutions of seven of the eight salts (CaSO<sub>4</sub>, gypsum, is not sufficiently soluble), using the unfilled, waterproofed, top 6.35 cm of

the cylinders to contain the solutions. Infiltration seldom took more than 24 hours. They were then dried again in the oven for 48 hours at 43°C. Three more wetting and drying cycles were completed in the same manner for a total of four cycles.

The dehydrated mass of total salts added was kept constant. They were dissolved in deionized water in concentrations such that 115 ml of the solution contained a weight of the salt in its dehydrated state equivalent to either 2, 1, or 0.5% of the oven dry weight (605 g) of the adobe material in the cylinders. The weights of hydrated salts used ( $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  and  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ ) were adjusted to a dehydrated basis. The 115 ml volume infiltrated in each wetting cycle was the volume of liquid the sample and cylinder absorbed with little or no leaching. Thus the maximum weight of dehydrated salt added to each sample after four cycles was either 8, 4, or 2% of the dry weight of adobe in the sample.

Gypsum samples were prepared by adding powdered  $\text{CaSO}_4$  equivalent to 8, 4, or 2% of the oven dry weight of the standard adobe batch before mixing and packing. They were then exposed to the same wetting and drying cycles as the other samples except that a saturated  $\text{CaSO}_4$  solution was used to encourage crystal growth.

Cylinders were also prepared employing amended test soil whose cation exchange capacity (CEC) was saturated with

either Ca, Mg, K, or Na. The test soil was leached with at least three pore volumes of a one-molar solution of the chloride of the particular cation. Then it was leached with deionized water until the electroconductivity of the leachate approached that of deionized water. These samples received no further treatment after initial packing and drying.

Other cylinders were subjected to four wetting and drying cycles with deionized water. There were also controls not treated after initial curing and drying.

#### Testing of the Treated Samples

Samples were removed from the cylinders by unraveling the cardboard spirals and were evaluated visually for cracking and general condition.

Lambe (1951) points out that the shear strength of a cohesive soil is made up of a frictional component and a cohesive component, but that the term cohesion is often used loosely for the shear strength of a soil when tested with no lateral load applied to the specimen. He further notes that the unconfined compression test is the simplest and quickest laboratory method commonly used to measure the shear strength of a cohesive soil. The unconfined compression test was used to evaluate the effects of the various treatments on the strength of the specimens.

All specimens were allowed to cure for at least two weeks in the laboratory before testing. The samples that remained sufficiently intact were cut to a length of 6.35 cm with a masonry saw. The  $MgCl_2$  and  $CaCl_2$  treatments had to be dried first at  $105^\circ C$  because retention of water by the salts made them too unstable to saw. The resulting surfaces of all treatments were neither smooth nor parallel, so it was necessary to cap both ends for consistency in testing. Molten sulfur was used. Appendix C gives details of the method devised.

Approximately half of the capped samples were immediately tested for compressive strength in an air-dry condition in a hydraulically powered Soil Test Versa Tester apparatus, employing a slow loading rate (0.66 cm/min). Time to failure ranged from 20 seconds to 3.5 minutes. Moisture contents were determined for a representative portion of one sample from each treatment.

Twenty g of the oven dried soil were removed from the moisture content samples and were agitated for one hour with 100 ml of deionized water. Soluble salt contents were determined for all samples by comparing the electroconductivities of the resulting solutions with previously prepared graphs relating known concentrations of each dehydrated salt to the corresponding electroconductivity measurement.

The remaining samples were placed in a humidity chamber and maintained at 100% RH for 14 days. To encourage hydration and dehydration cycles, the temperature was raised from room temperature (23°C) to approximately 36°C each day by switching on a light bulb in the chamber for four hours.

The samples were tested for compressive strength immediately upon removal from the chamber. Moisture contents were also measured on all samples immediately after compressive strength testing. Their salt contents were determined in the same manner as the air-dry samples.

## RESULTS AND DISCUSSION

### Stability of the Adobe Cores

After treatment, the cores were evaluated visually, and consequently subjectively, as to the extent of cracking and their general stability.

Control cores that were untreated after packing and drying the cylinders showed the effect of the initial drying. Figure 1 shows that all six control cores experienced one partial or complete horizontal crack 3 to 4 cm from the top, which was the major evaporative surface of the cylinders. These cracks are most likely the result of shrinkage of the expansive clay in the samples upon drying.

Other samples (Fig. 2) that were treated with four wetting and drying cycles with deionized water further support the concept that wetting and drying cycles promote cracking of adobe. All but one (H<sub>2</sub>O-D) exhibited a clear pattern of horizontal cracks in the top 8 to 9 cm of the cores, indicating a continuation of the pattern exhibited by the controls.

Two salts, calcium and magnesium chloride, retained moisture strongly enough to remain damp even after drying for 48 hours at 43°C. Compared to the untreated controls, the 8% and 4% treatments showed considerably more cracking and a crumbly aspect (Fig. 3). Reduction of cohesion

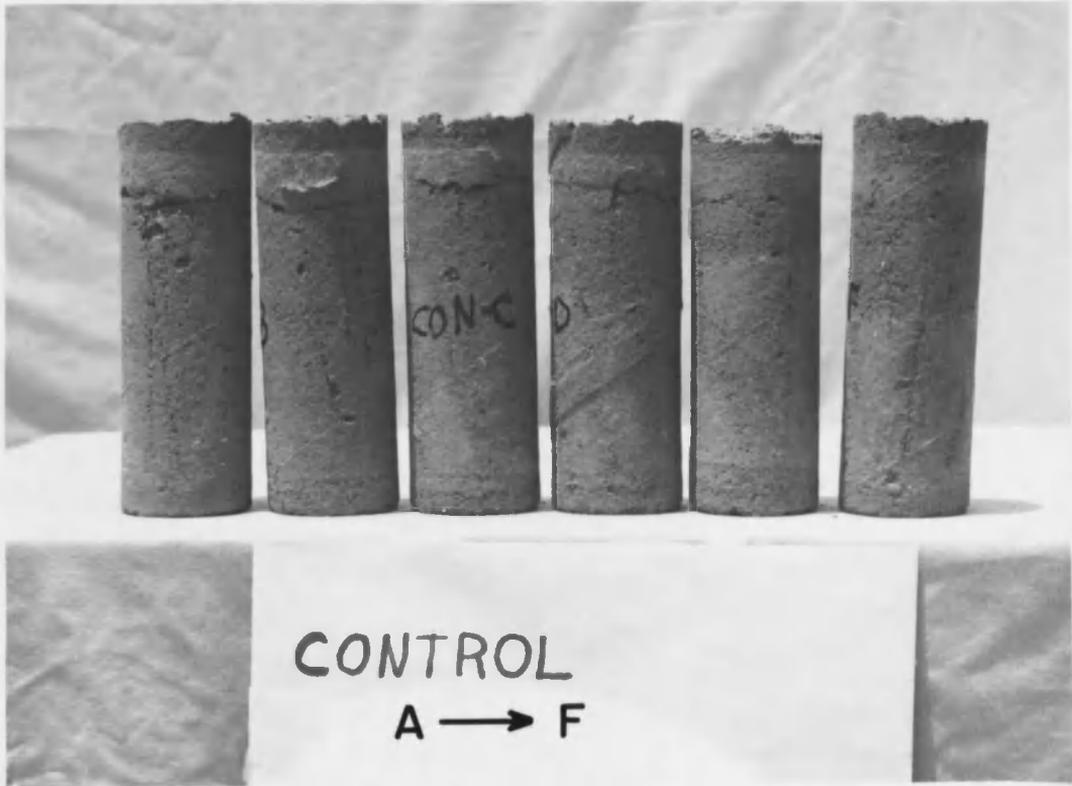


Fig. 1. Untreated control test adobe cores showing cracks from drying.



Fig. 2. Cracking patterns in adobe cores after four wetting and drying cycles.

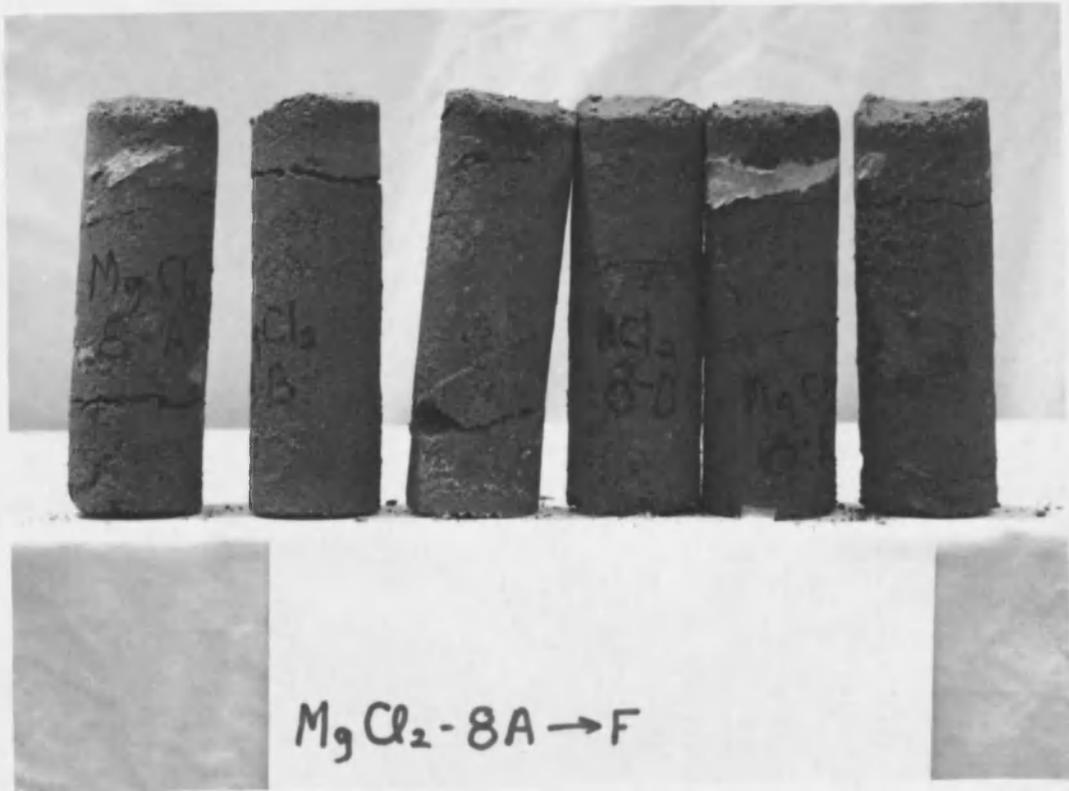


Fig. 3. Instability of  $\text{MgCl}_2$ -8% adobe cores from retention of moisture.

between soil particles by the retained moisture was responsible for at least some of the cracking. However, hydration pressures also played a role in promoting deterioration, at least in the case of the  $\text{CaCl}_2$ -8% treatments.

Figure 4 shows the  $\text{CaCl}_2$ -8% cores after about 14 days of exposure to laboratory conditions. The treatments emerged damp but generally intact from the cylinders, but as the  $\text{CaCl}_2$  gradually hydrated in the lower temperature and increased humidity of the laboratory, large portions of the samples disintegrated. The hydration pressures evidently were great enough to cause spalling of the weakened, damp samples. The  $\text{MgCl}_2$ -8% and -4% samples did not deteriorate to the same extent, but they generally became less stable after exposure in the laboratory.

Sodium sulfate and magnesium sulfate actually appeared to stabilize the cores. The 2% treatments were in about the same condition as the untreated controls, but less cracked than the cores subjected to wetting and drying with deionized water. The 4% treatments showed evidence of healing of cracks and the 8% treatments appeared to have cemented the cores into completely intact units. The cardboard cylinders were difficult to remove because of cementation to the cores.

Sodium chloride treatments showed somewhat more cracking than the untreated controls, especially the 2 and

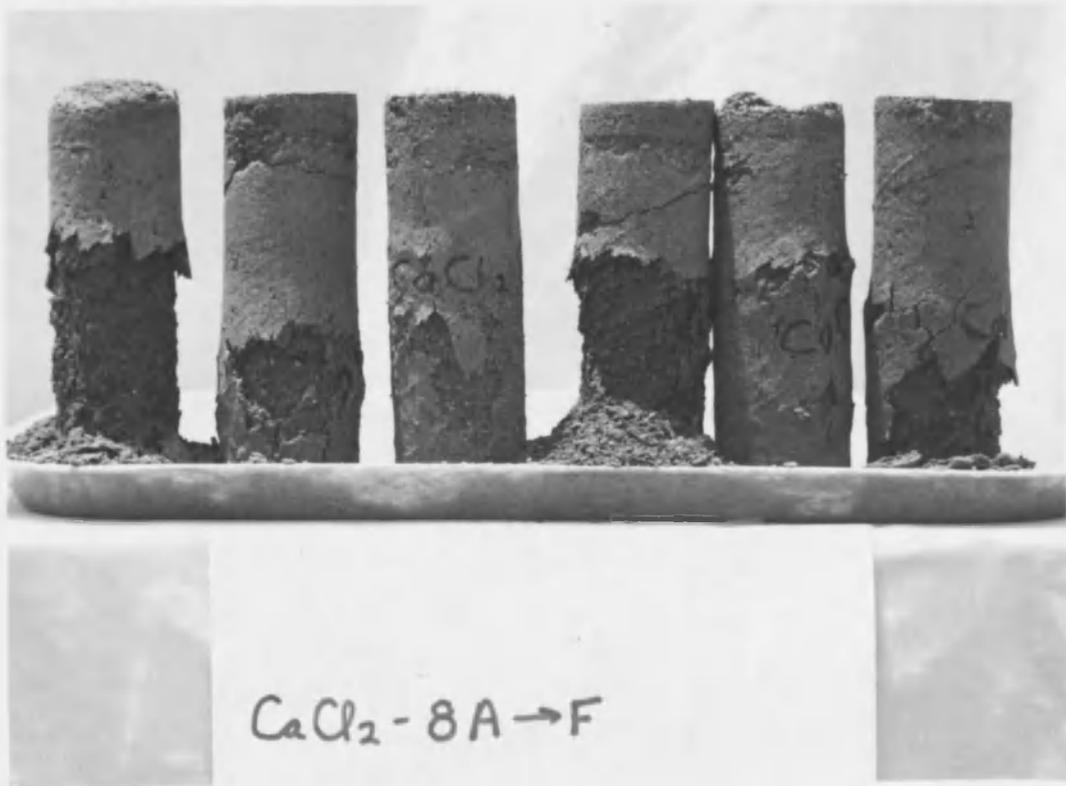


Fig. 4. Failure of  $\text{CaCl}_2$ -8% adobe cores because of retained moisture and hydration pressures.

4% treatments. Very possibly this is the result of the increased swelling potential exhibited by montmorillonite when it is saturated with the Na cation as compared to the other cations in this study. Increased swelling is more pronounced at lower salt concentrations since clay-to-clay repulsion is increased at lower concentrations (Quirk 1964).

The cation exchange capacity of the test soil was originally saturated predominantly with calcium as indicated by 60.2% exchangeable calcium (Table 2). Since the salt treatments resulted in adding at least four pore volumes of relatively concentrated salt solutions, it can be assumed that by the principle of mass action the cation exchange sites of the salt-treated cores became essentially saturated with the particular cation used in the treatment.

The top 3 to 4 cm of all potassium treatments, whether 8, 4, or 2%, or whether sulfate or chloride, completely lost physical coherence and crumbled to powder when the cores were removed from the cylinders. Electroconductivity measurements of extracts from the powder showed a wide range of salt contents (0.3 to 4%), but there was very little variation in the effect, indicating that crystallization pressures were not responsible. Furthermore, the cores that had been formed from K-CEC saturated test soil leached of soluble salts were extremely cracked and generally unstable (Fig. 5).



Fig. 5. Instability of K-CEC saturated adobe cores.

The simple presence of a K-saturated colloidal system appears to be sufficient to cause instability in the particular soil tested. One possible explanation is that, as Ravina (1973) observed, the illite (and possibly montmorillonite) platelets curled on drying and thereby disrupted the forming, or reforming, fabric.

Other than the instability of the top of the cores, the  $K_2SO_4$  and KCl samples did not appear to be adversely affected.

Samples formed by mixing 8, 4, or 2% powdered  $CaSO_4$  with the adobe mix before packing the cylinders were somewhat more cracked than the untreated controls (similar to the NaCl cores), but it is not known whether this reflects the influence of the  $CaSO_4$  itself or simple physical interference to fabric formation by the fine powder.

Unconfined Compressive Strengths,  
Air-Dry and Humidified

Only the  $CaCl_2$ -8% and the K-CEC saturated cores were too unstable to allow recovery of intact samples. In most cases it was possible to obtain an intact, uncracked 6.35 cm length of core (5.08 cm diameter) by cutting the sample core with a masonry saw. Some of the cores were totally intact, and others were cracked to various degrees but were sufficiently coherent to obtain a sample for testing. Therefore, the compressive strength measurements obtained do not

necessarily reflect the stability of the total specimen, but rather the strength of one particular coherent section.

About half the cores of each treatment were tested in an air-dry condition. The remaining samples were tested after exposure to 100% relative humidity for 14 days. All samples were analyzed for salt content. All of the humidified samples and one sample from each treatment of the air-dry samples were evaluated for moisture content. Values obtained are recorded in Appendix A and Appendix B.

#### Untreated Controls

Figure 6 gives the average and range of the compressive strengths of the untreated controls. The results of the other treatments were compared against these values. Adsorption of moisture by the humidified samples weakened them considerably, but their strength was still much greater than the  $3.5 \text{ kg/cm}^2$  ( $50 \text{ lb/in}^2$ ) that Clifton and Davis (1977) feel is the minimum safe limit of the compressive strength of Tumacacori adobe.

#### Wetting and Drying Cycles

Values obtained from cores exposed to four wetting and drying cycles with deionized water (Fig. 7) were very similar to those of the untreated controls, indicating that when wetting and drying cycles do not cause cracking, strength is little affected.

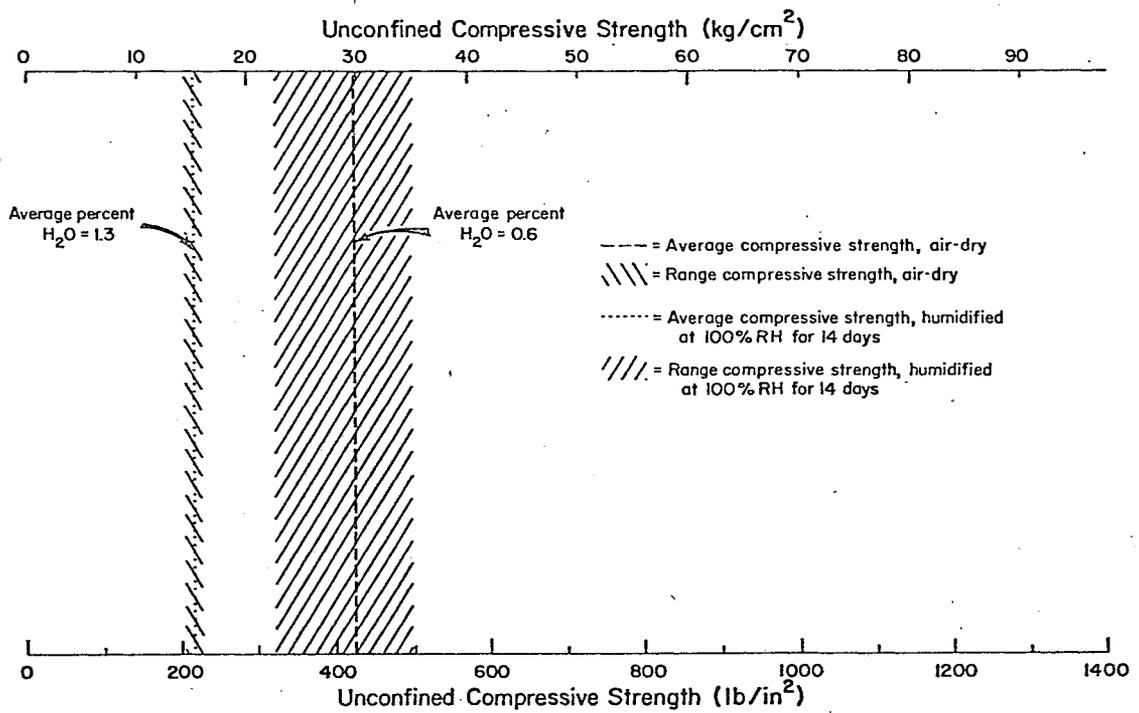


Fig. 6. Average unconfined compressive strength and range of compressive strength for untreated adobe cores.

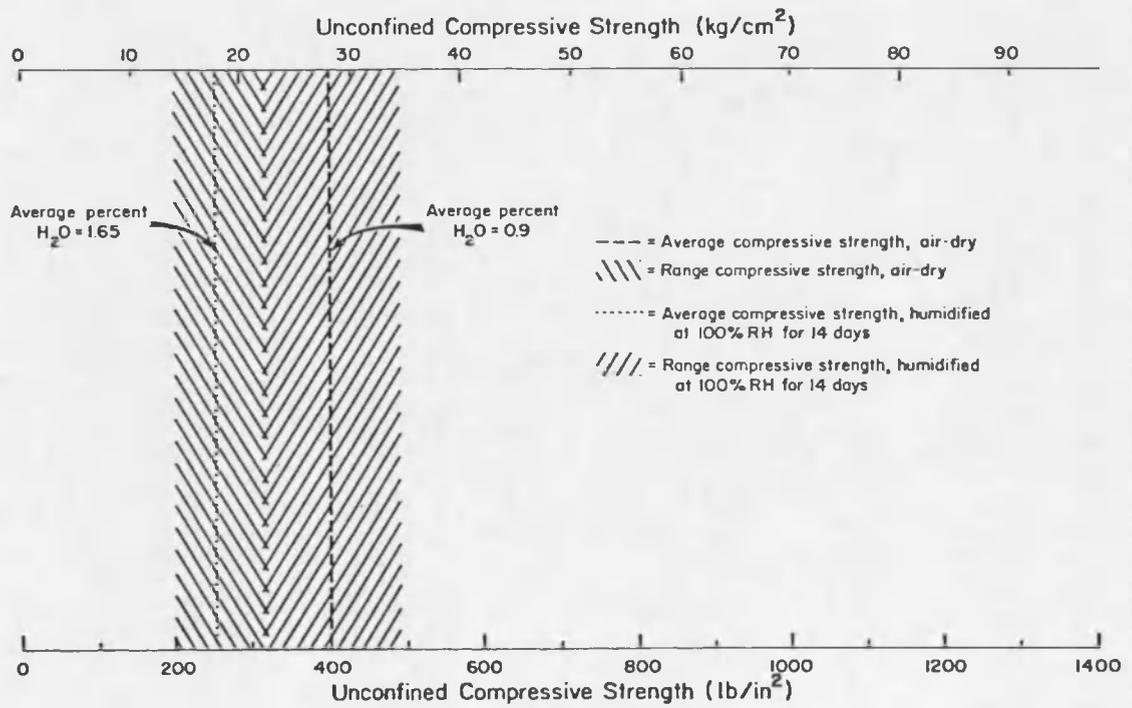


Fig. 7. Average unconfined compressive strength and range of compressive strength for adobe cores subjected to four wetting and drying cycles with deionized water.

## Cation Exchange Capacity Saturation Effects

Saturation of the cation exchange capacities of the adobe cores (no soluble salts) resulted in the following order of average air-dry compressive strengths: calcium > (37.3 kg/cm<sup>2</sup>) > magnesium (35.9 kg/cm<sup>2</sup>) > sodium (22.9 kg/cm<sup>2</sup>) > potassium (failed). The humidified samples followed the same pattern and proportionality.

Baver et al. (1972) note that divalent cations compress the diffuse double layer surrounding clay particles more than monovalent cations. This compression lessens the clay-to-clay repulsive forces and should therefore allow closer approach of clay particles during fabric formation. Since cohesive forces in soil are extremely short-ranged, this may explain why divalent Ca and Mg produced in this instance a stronger fabric than the monovalent Na. Potassium appears to exert a disruptive effect on the fabric quite apart from any weakening that might be caused by its monovalence.

## Calcium Chloride (CaCl<sub>2</sub>) and Magnesium Chloride (MgCl<sub>2</sub>)

Figures 8 and 9 clearly indicate that the presence of even a small amount of either CaCl<sub>2</sub> or MgCl<sub>2</sub> seriously weakens the strength of adobe by retention of moisture. The amount of moisture retained relates directly to the

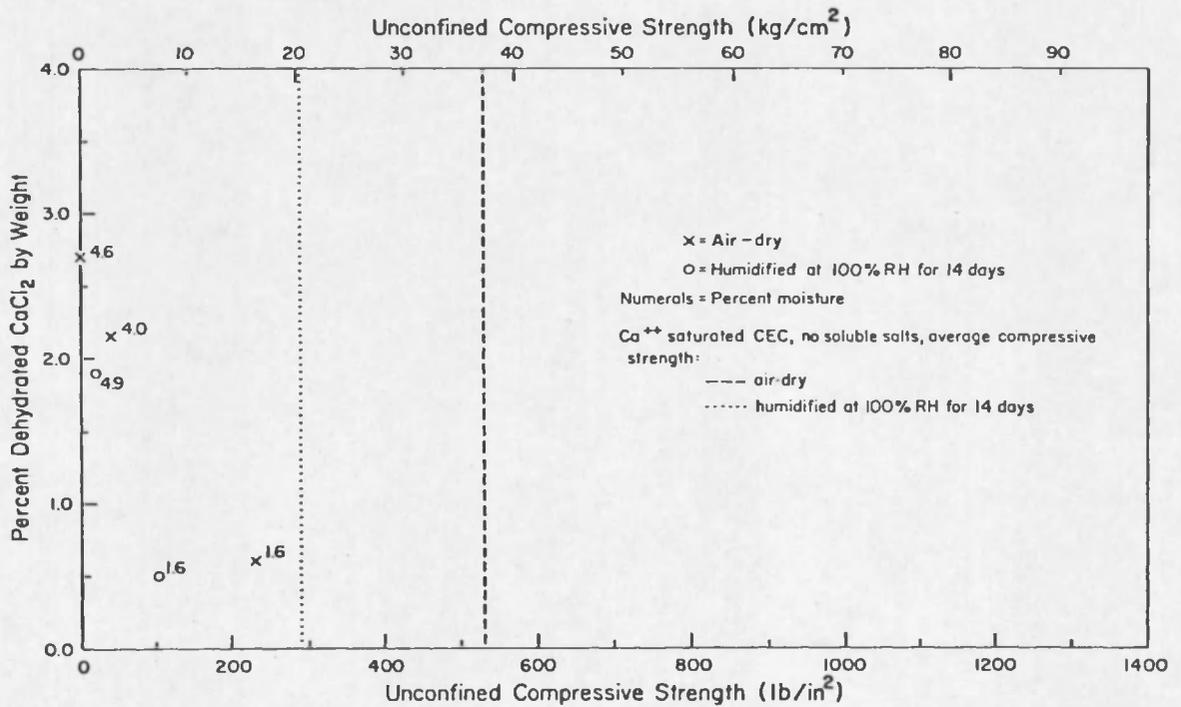


Fig. 8. Unconfined compressive strength of adobe cores relative to  $\text{CaCl}_2$  and moisture contents, with average compressive strengths of  $\text{Ca}$ -CEC saturated cores.

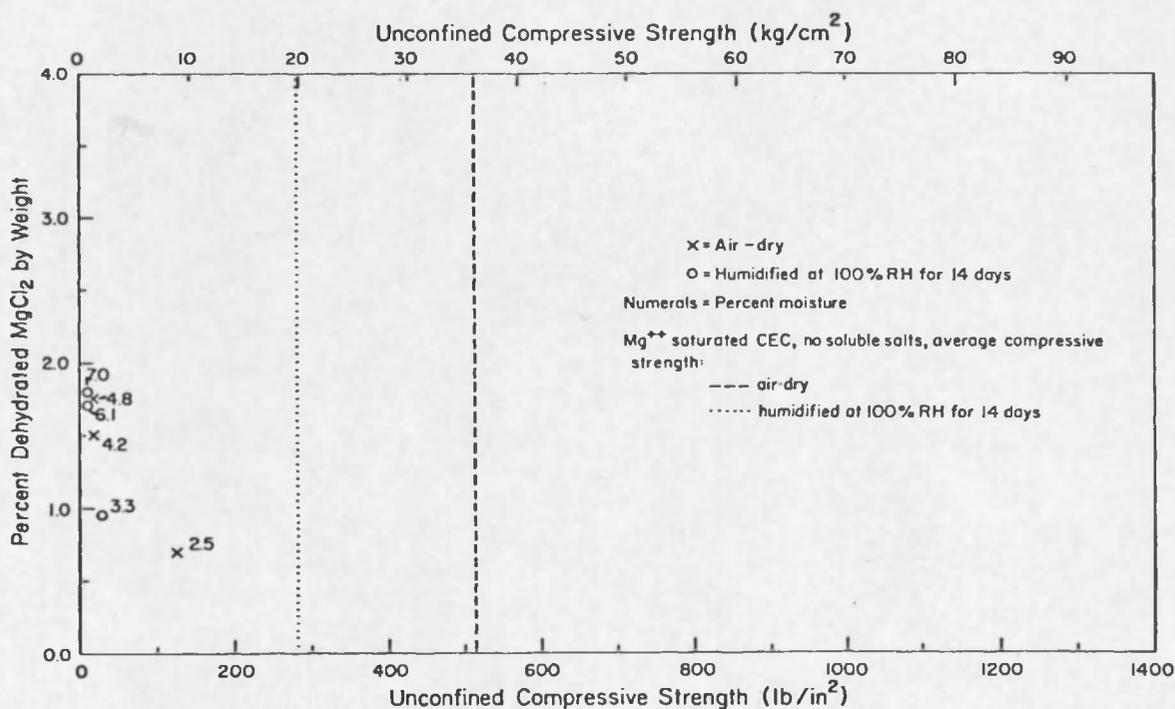


Fig. 9. Unconfined compressive strength of adobe cores relative to  $\text{MgCl}_2$  and moisture contents, with average compressive strengths of Mg-CEC saturated cores.

amount of salt. The compressive strength relates inversely to both.

At a salt content of over 2.5%, slow hydration of  $\text{CaCl}_2$  caused extensive failure of the cores (Fig. 4). The hydration pressures appeared weak but persistent as the cores spalled over 10 to 14 days. Realistically, adobe failure due to hydration of  $\text{CaCl}_2$  probably would only occur fairly near the surface of a wall where confining pressures were small and temperature and humidity fluctuations greatest.

No sample of  $\text{MgCl}_2$  exceeded 1.8% salt, so it remains unclear whether or not hydration failure similar to that of the more saline  $\text{CaCl}_2$  samples might occur.

Since the strengths of all treatments of both salts were well below those recorded for the Ca- and Mg-CEC saturated treatments, the simple presence of the cations on the cation exchange complex was not responsible for the low strengths of the salt-saturated treatments.

#### Magnesium Sulfate ( $\text{MgSO}_4$ )

In its air-dry state  $\text{MgSO}_4$  exhibits by far the strongest cementing action of all the salts. Less than 2% salt content produced strengths more than double that of the average of the untreated controls (Fig. 10). Increasing salt content produced greater strength far beyond the effect of Mg on the cation exchange complex.

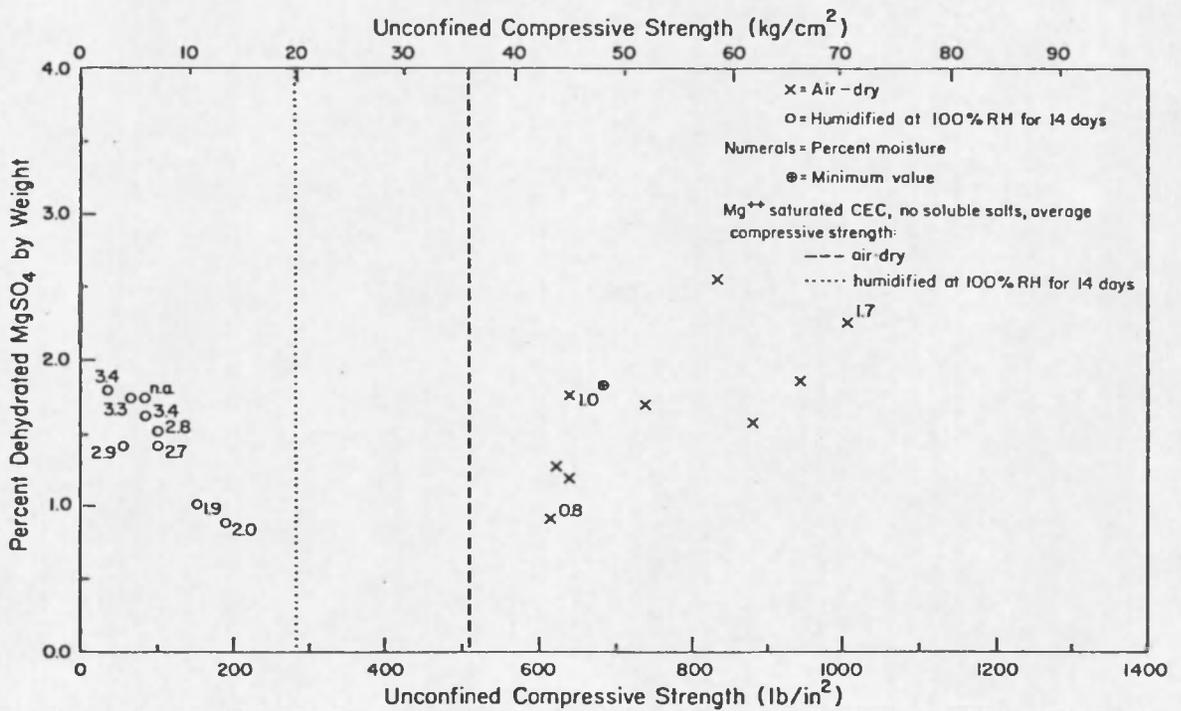


Fig. 10. Unconfined compressive strength of adobe cores relative to MgSO<sub>4</sub> and moisture contents, with average compressive strengths of Mg-CEC saturated cores.

Under humidified conditions  $MgSO_4$  behaved as a hygroscopic salt, though it did not adsorb moisture as readily as the chlorides.

#### Sodium Chloride (NaCl)

Sodium chloride (Fig. 11) was detrimental to the strength of the test adobe under both air-dry and humidified conditions. Saturation of the cation exchange complex with Na lowered the strength of the air-dry samples by affecting fabric formation, as was indicated by the relatively low strength of the Na-CEC saturated samples.

Humidification reduced the compressive strength of all NaCl samples to less than  $0.7 \text{ kg/cm}^2$  (10 psi). A salt content of only 1.25% resulted in adsorption of 9.3% moisture.

#### Potassium Chloride (KCl) and Potassium Sulfate ( $K_2SO_4$ )

Potassium chloride (Fig. 12) behaved essentially like NaCl, except that it is somewhat less hygroscopic. Saturation of the cation exchange complex with K weakened the samples relative to Ca- and Mg-CEC saturated treatments (Figs. 8 and 9), but since the K-CEC saturated samples were too unstable to test no average strengths were obtained for those treatments.

In its air-dry state  $K_2SO_4$  (Fig. 13) decreased the strength of the samples relative to the untreated controls

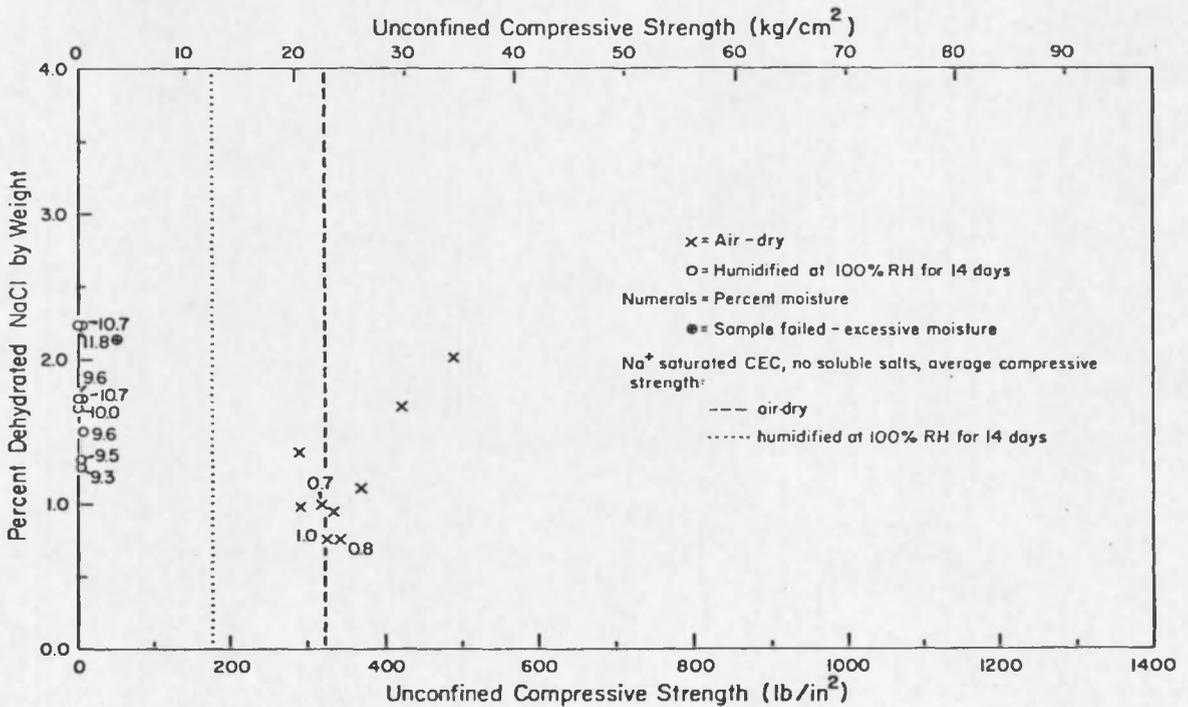


Fig. 11. Unconfined compressive strength of adobe cores relative to NaCl and moisture contents, with average compressive strengths of Na-CEC saturated cores.

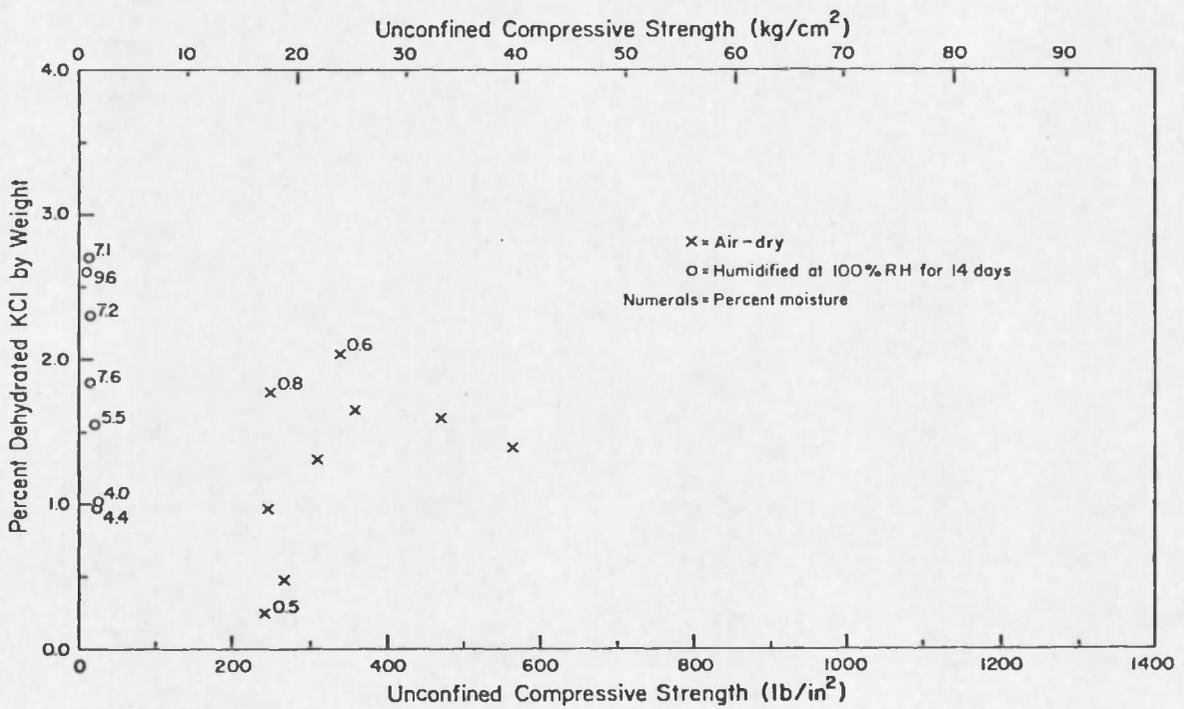


Fig. 12. Unconfined compressive strength of adobe cores relative to KCl and moisture contents, values for K-CEC saturated cores unavailable.

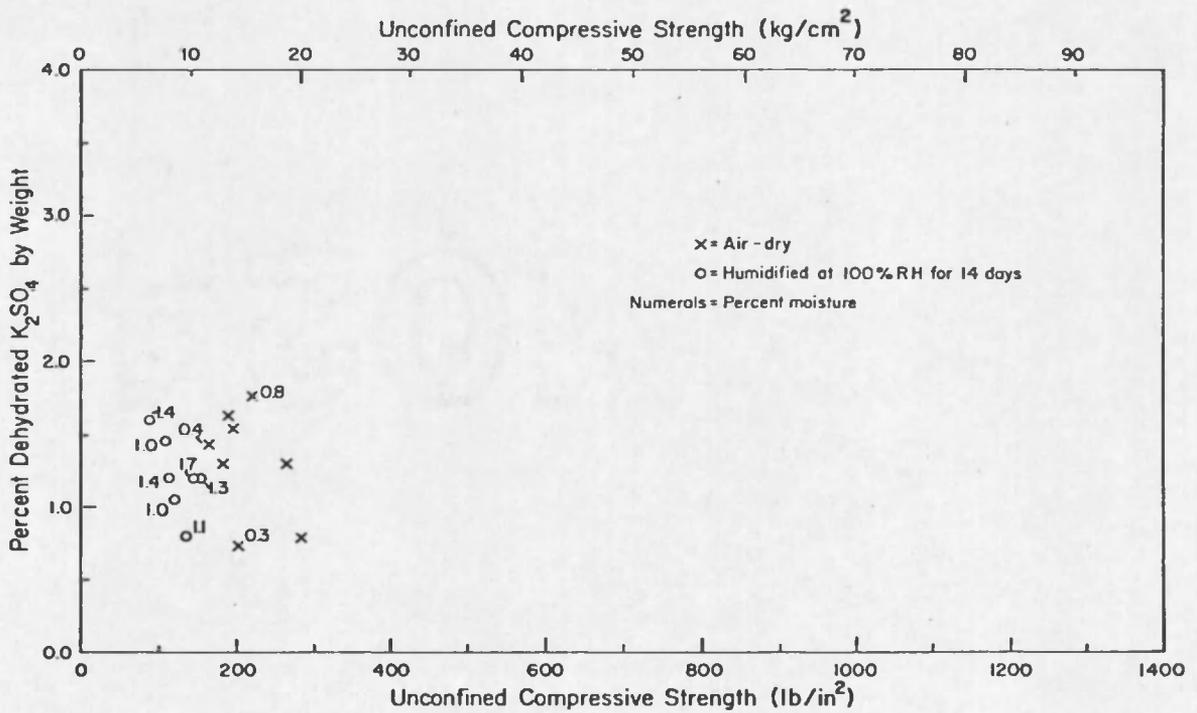


Fig. 13. Unconfined compressive strength of adobe cores relative to K<sub>2</sub>SO<sub>4</sub> and moisture contents, values for K-CEC saturated cores unavailable.

even more than the KCl treatments. However, humidification resulted in only a small further reduction in strength, since  $K_2SO_4$  showed little affinity for hygroscopic moisture.

Potassium sulfate is neither a hydrating nor a hygroscopic salt. Thus, K-CEC saturation of the clay probably accounts for the generally low strength of the treatments. The fact that the samples decrease in strength with increasing salt content (and presumably per cent K-CEC saturation) supports this conclusion. On the other hand, KCl air-dry treatments showed increasing strength with increasing soluble salt content, indicating a mild cementing effect.

#### Sodium Sulfate ( $Na_2SO_4$ )

Winkler and Wilhelm (1970) note that sodium sulfate hydrates and dehydrates much more rapidly than most salts and therefore is potentially very destructive, especially when exposed to rapid changes in temperature and/or humidity. They report that maximum damage done to Cleopatra's Needle, an ancient Egyptian stone obelisk brought to New York in 1881, occurred in the months of March through May when the relative humidity is high and temperature changes are rapid.

They further state that thenardite ( $Na_2SO_4$ ) is stable at  $32.4^\circ C$  or greater, and that mirabilite ( $Na_2SO_4 \cdot 10 H_2O$ ) is stable from  $0-32.4^\circ C$ . The transformation is

rapid--at 39°C the dehydration of mirabilite to thenardite takes no longer than 20 minutes. At 23°C this hydration is capable of producing pressures of about 400 atmospheres.

Doner and Lynn (1977) confirm the ability of  $\text{Na}_2\text{SO}_4$  to hydrate and dehydrate under common conditions. They report that in salt deposits in arid regions mirabilite is always found a few cm below the soil surface, while thenardite is encountered on the surface. Furthermore, in winter the thenardite is transformed to mirabilite. The potential for surface spalling of adobe containing  $\text{Na}_2\text{SO}_4$  is evident.

In this experiment the temperature in the humidity chamber was cycled daily from room temperature (about 23°C) to approximately 36°C in order to induce hydration and dehydration cycles.

Results from the humidified samples confirmed that  $\text{Na}_2\text{SO}_4$  is capable of developing hydration pressures under the test conditions sufficient to destroy adobe fabric. Three of the nine samples showed cracking, bulging, or bursting (Fig. 14). Moreover, the  $\text{Na}_2\text{SO}_4$  adsorbed a moderate amount of hygroscopic moisture, thus weakening the sample fabric.

Under air-dry conditions  $\text{Na}_2\text{SO}_4$  appeared to have little effect on the samples.

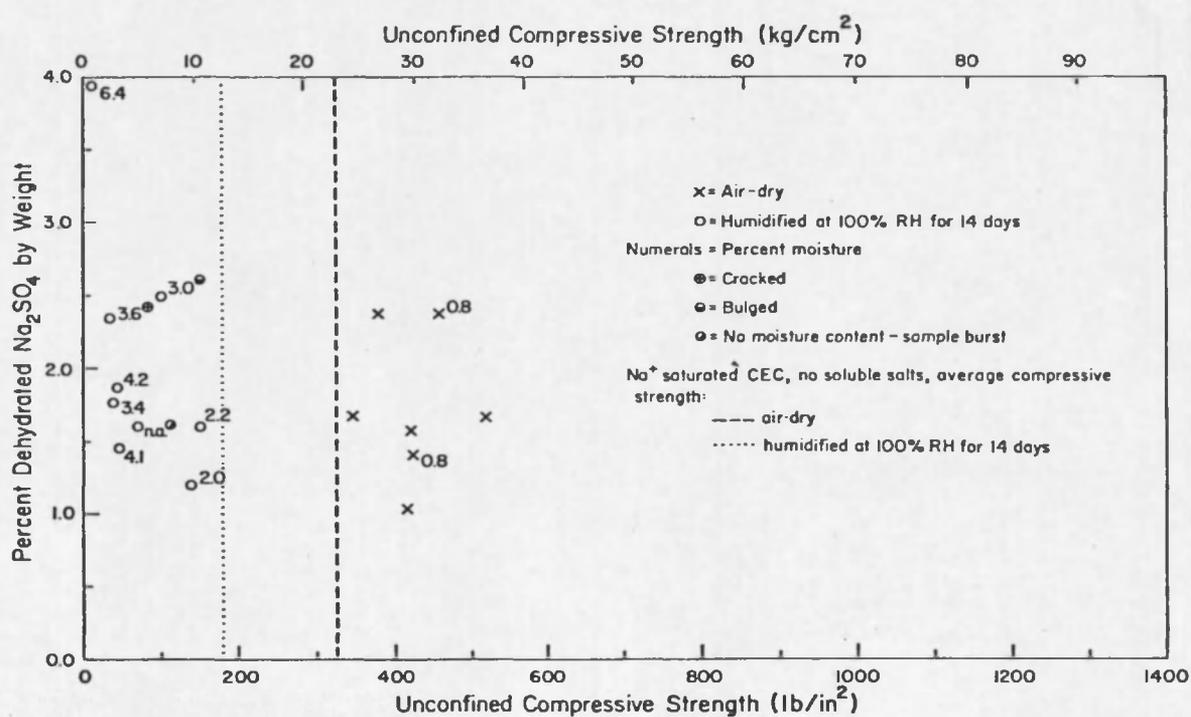


Fig. 14. Unconfined compressive strength of adobe cores relative to Na<sub>2</sub>SO<sub>4</sub> and moisture contents, values for K-CEC saturated cores unavailable.

Calcium Sulfate ( $\text{CaSO}_4$ )

Table 3 shows that the  $\text{CaSO}_4$  treatments did not result in lowering the adobe strength to a critical level. Neither hydration pressures nor adsorption of hygroscopic moisture appear to be problems. Winkler (1975) indicates that bassanite ( $\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$ ) is stable at 60 to 90°C, while gypsum ( $\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$ ) is stable below 60°C. Since 60°C is never reached in the walls of Tumacacori (nor was approached in this experiment), the potentially substantial hydration pressures of  $\text{CaSO}_4$  would seem not to be a factor in deterioration of adobe.

Table 3. Average Unconfined Compressive Strengths and Moisture Contents of  $\text{CaSO}_4$  Treatments

Treatment	Average Air-Dry Strength	Average Humidified Strength <sup>a</sup>	Average Moisture Content, Humidified Samples
% salt added	-----kg/cm <sup>2</sup> -----		%
8	18.6	9.3	1.5
4	18.3	12.2	1.5
2	19.8	13.5	1.5

<sup>a</sup>100% RH for 14 days.

Little else should be inferred from these results since the  $\text{CaSO}_4$  treatments were not formed or treated in the same manner as the other samples.

#### Effects of Salts on Wetting and Drying Cycles

The most noticeable effects of wetting and drying cycles were observed in the cores subjected to these cycles with deionized water. In the salt treated cores the horizontal cracking pattern observed in the deionized water treatments generally decreased with increasing salt content. These results are in complete accord with the double layer theory, which predicts limitation of clay swelling with increasing salt content (Baver et al. 1972).

#### Anionic Effects

In contrast to adsorbed cations, the chloride and sulfate anions do not directly affect the formation of adobe structure. In general the common chloride salts are more deleterious to adobe stability than the sulfates because they have more affinity for moisture. Under air-dry conditions none of the sulfate treatments retained significant moisture, but  $\text{CaCl}_2$  and  $\text{MgCl}_2$  did. All the chlorides were very hygroscopic under highly humidified conditions, while of the sulfates only  $\text{MgSO}_4$  and  $\text{Na}_2\text{SO}_4$  were moderately hygroscopic.

### Crystallization Pressures

Evans (1969-1970) reports that crystallization pressures of soluble salts are sufficient to overcome the tensile strength of stone. Brown et al. (1978) feel that crystal growth of gypsum, and possible other salts, ultimately leads to severe disruption of the adobe matrix.

No evidence emerged from this study to indicate that salt crystallization disrupts adobe fabric. In no case did crystal accumulations in cracked samples appear to be the cause of the fault. In no case were cores deformed or burst from such pressures.

The seeming contradiction deriving from the fact that salt crystallization can destroy stone but not adobe can be explained by the nature of the two materials. Stone is incapable of sustaining significant deformation without breaking because of its brittle nature. On the other hand, adobe is moist and yielding at the time when crystallization pressures develop. Since the typical adobe has 30 to 40% pore space, there is ample room to accommodate crystal growth.

It is possible that the four wetting and drying cycles used in this experiment were insufficient to develop crystals of sufficient size to overcome the strength of the adobe fabric. It is also possible, even probable, that near-surface crystallization of salts (subfluorescence) contributes to spalling of the adobe surface. However, the

results of this study indicate that crystallization pressures do not seriously disrupt the fabric of confined adobe, that is, adobe other than surface material.

#### Hydration Pressures

Sodium sulfate was effective in bursting the test adobe fabric principally because it hydrates and dehydrates rapidly under conditions of temperature and humidity commonly encountered in diurnal fluctuations, and because the fabric was relatively dry and brittle when the pressures developed.

Calcium chloride (and possibly  $MgCl_2$ ) do not hydrate rapidly, but they retain so much hygroscopic moisture that slow hydration is sufficient to cause considerable surface deterioration.

#### Hygroscopicity

All the salts tested, with the exception of  $K_2SO_4$  and  $CaSO_4$ , were at least moderately hygroscopic when exposed to high humidity, and consequently reduced the strength of the test adobe. The chlorides were especially detrimental. There can be no doubt that accumulations of common soluble salts significantly weaken adobe under highly humid conditions.

### Patternization of Salts

Adobe samples in this experiment were treated with pure salts rather than mixtures of salts in order to isolate specific effects and because there is virtually an infinite number of combinations possible. Moreover, evidence exists to suggest that patternization, that is, concentrations of specific salts in specific areas of a structure, is quite possible. Thus, a particularly disruptive salt such as NaCl or  $\text{Na}_2\text{SO}_4$  present in relatively small amounts nevertheless might create structural weakness if concentrated in a critical area.

Present knowledge of the soil-water-salt system is insufficient to predict patternization of salts. Only experimentation in the field duplicating the particular situation of interest can provide usable information on patternization of salts.

### A Concept of Salt Accumulation Limits

A minimum of 2% and a maximum of 8% of the dry sample adobe weight was added to the test cores by infiltration of four 115 ml volumes of solution. Most treatments experienced very little leaching after absorption of the solutions by the adobe core and its containing cylinder. However, if one isolated instance of relatively high salt content (3.9%  $\text{Na}_2\text{SO}_4$ ) and the lowest salt content (0.25%

KCl) are eliminated from consideration, the range of salt content is only 0.45 to 2.7%.

All the salts except the strongly hydrated  $\text{CaCl}_2$  and  $\text{MgCl}_2$  produced substantial encrustations on the surface of the cylinders. They experienced very little leaching. The  $\text{CaCl}_2$  and  $\text{MgCl}_2$  samples were leached to a greater degree than the other treatments since they retained considerable moisture after the drying cycles. In general, the 2% treatments of all salts retained a higher percentage of salt added than the 4% treatments, which in turn retained almost as much as the 8% treatments.

This study did not investigate this phenomenon in detail so specific mechanisms cannot be suggested. However, it does appear that adobe free to transfer fluids (almost always the case) possesses properties that tend to limit the accumulation of soluble salts.

#### A Suggested Development in the Concept of Adobe Fabric

The fabric of naturally occurring soils can serve only as a theoretical basis for understanding adobe fabric. As Rosenqvist (1963) points out, the bulk properties of virgin sediments differ from those of chemically or mechanically altered clays. Adobe makers know that a certain amount of mechanical mixing is necessary to produce stable adobe. One reason is that mixing breaks down the ped structure, common in most soils, in which aggregates

smaller than adobe size are only loosely held together. Also, the larger pores are reduced in number, the mass becomes more dense, and there is increased skeleton grain contact (Lafeber 1964).

It is proposed that there is yet another mechanism produced by mechanical mixing that helps produce a coherent adobe fabric. Kirkpatrick and Rennie (1973), Lafeber (1964), and others have noted that clay platelets tend to be oriented parallel to shear planes, such as those produced by mixing. These "ribbons" of clay are more oriented and denser than the surrounding fabric. Since the oriented clays along the shear plane are closer to each other and present more surface area to each other as compared to the surrounding fabric, it is logical to assume that these shear planes possess a stronger dry fabric.

Kirkpatrick and Rennie (1973) further report that the remolding of kaolin by kneading aligned the particles in narrow bands which were subsequently bent and rotated into complex three dimensional shapes, producing complex structure forms which are unrelated to those associated with natural clays.

This intertwining of oriented shear planes may be an important mechanism in producing a coherent adobe mass. Perhaps a rough analogue is felt cloth, which is held together solely by the mechanical intertwining of its fibers. It is further suggested that the method of mixing

adobe may be instrumental in determining the durability of the adobe produced and that new mixing methods might be developed that could produce a superior adobe material.

## SUMMARY AND CONCLUSIONS

At Tumacacori Mission sections of the adobe walls exposed to capillary moisture and soluble salt accumulations show obvious surface deterioration, while unaffected portions are intact.

Since different adobe materials can react quite distinctly to the changing solution environment caused by the influx of moisture and salts, the test adobe was matched as closely as possible to the original Tumacacori adobes in regards to clay minerology, particle size distribution, and exchangeable cations.

Adobe cores were formed in porous cardboard cylinders. Original moisture contents, densities, and method of mixing and packing were standardized. Cylinders were exposed to four wetting and drying cycles with solutions of the chlorides and sulfates of Ca, Mg, K, and Na (except  $\text{CaSO}_4$ ) in such a way as to encourage crystal growth. Other treatments include  $\text{CaSO}_4$  and cylinders prepared from test soil whose CEC was saturated with one of the four cations (no soluble salts). Other cylinders were subjected to wetting and drying with deionized water, and there were controls not treated after initial formation.

About half the cores were tested for unconfined compressive strength in an air-dry condition. The remaining samples were tested after exposure to 100% RH for 14 days.

Compressive strength measurements and visual evaluation of the cores indicate:

1. Wetting and drying cycles produced cracking patterns parallel to and associated with the major unconfined surface of adobe.
2. When wetting and drying cycles did not produce cracking (such as in the confined interior of an adobe wall), compressive strength was little affected.
3. Increasing the salt content tended to minimize cracking from wetting and drying cycles.
4. Saturation of the CEC of the test soil resulted in the order of average compressive strengths:  
Ca-Mg > Na > K.
5. Disintegration of portions of all K treatments appeared to be caused by a change in adobe fabric resulting from substitution of Ca and Mg on the CEC by K.
6. Under prolonged conditions of high humidity, all salts except  $K_2SO_4$  and  $CaSO_4$  adsorbed considerable hygroscopic and/or hydrated moisture and seriously weakened the adobe. Chlorides adsorbed more than sulfates.

7. Retention of moisture under laboratory conditions was minimal except for  $\text{CaCl}_2$  and  $\text{MgCl}_2$  treatments.
8. Sodium sulfate  $\text{Na}_2\text{SO}_4$  and  $\text{CaCl}_2$  developed hydration pressures sufficient to cause surface spalling of adobe.
9. The deformability and porosity of damp adobe prevented deterioration by crystallization pressures, although such pressures may affect surface material.
10. Magnesium sulfate  $\text{MgSO}_4$  exhibited a strong cementing effect in the air-dry state.
11. For practical purposes, deterioration caused by wetting and drying cycles and soluble salt accumulations is limited to surface and near-surface adobe material.

Literature review and observations suggest:

1. Segregation of salts in an adobe wall because of differential mobilities and solubilities is a distinct possibility.
2. As salt content in adobe increases, so may the tendency to transfer the salt, thereby limiting the accumulation in the interior of an adobe wall.
3. Improving the method of mixing adobe may lead to production of a superior adobe material.

APPENDIX A

UNCONFINED COMPRESSIVE STRENGTHS, SALT, AND  
MOISTURE CONTENTS OF AIR-DRY CORES

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
CaCl <sub>2</sub> -8%	0--all specimens failed		average = 2.7	average = 4.6
CaCl <sub>2</sub> -4%	39	2.7	2.15	4.0
CaCl <sub>2</sub> -2%	251	17.6	0.6	1.6
Ca saturated	578	40.4	<0.1	0.7
	536	37.5	<0.1	--
	479	33.5	<0.1	--
MgCl <sub>2</sub> -8%	22	1.5	1.75	4.8
MgCl <sub>2</sub> -4%	22	1.5	1.5	4.2
MgCl <sub>2</sub> -2%	124	8.7	0.7	2.5
Mg saturated	461	32.3	<0.1	0.6
	481	33.7	<0.1	--
	589	41.2	<0.1	--
NaCl-8%	322	22.5	1.0	0.7
	491	34.4	2.0	--
	422	29.5	1.65	--
NaCl-4%	328	23.0	0.75	1.0
	334	23.4	0.95	--
	290	20.3	1.35	--

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
NaCl-2%	371	25.0	1.1	--
	340	23.8	0.75	0.8
	293	20.5	1.0	--
Na saturated	330	23.1	<0.1	0.6
	344	24.1	<0.1	0.6
	304	21.3	<0.1	0.6
KCl-8%	554	38.8	1.4	--
	341	23.9	2.05	0.6
	469	32.8	1.6	--
KCl-4%	251	20.1	1.8	0.8
	310	21.7	1.3	--
	359	25.1	1.65	--
KCl-2%	246	17.2	1.0	--
	268	18.8	0.5	--
	239	16.7	0.25	0.5
K saturated	too badly cracked to obtain sample			
Na <sub>2</sub> SO <sub>4</sub> -8%	458	32.1	--	--
	344	24.1	1.7	--
	461	32.3	1.85	0.8
Na <sub>2</sub> SO <sub>4</sub> -4%	456	31.9	--	--
	415	29.1	1.05	--
	518	36.3	1.7	--

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
Na <sub>2</sub> SO <sub>4</sub> -2%	378	26.5	1.85	--
	429	30.0	1.55	--
	434	30.4	1.4	0.8
MgSO <sub>4</sub> -8%	832	58.2	2.55	--
	1008	70.6	2.25	0.3
	946	66.2	1.85	--
MgSO <sub>4</sub> -4%	739	51.7	1.75	--
	640	44.8	1.85	1.0
	880	61.6	1.6	--
MgSO <sub>4</sub> -2%	622	43.5	1.3	--
	616	43.1	0.95	0.8
	640	44.8	1.15	--
CaSO <sub>4</sub> -8%	273	19.1	8	--
	270	18.9	8	--
	248	17.4	8	0.9
CaSO <sub>4</sub> -4%	257	18.0	4	--
	275	19.3	4	0.5
	248	17.4	4	0.5
CaSO <sub>4</sub> -2%	271	19.0	2	--
	293	20.5	2	0.6
K <sub>2</sub> SO <sub>4</sub> -8%	189	13.2	1.6	--
	186	13.0	1.3	0.4
	220	15.4	1.75	0.8

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
K <sub>2</sub> SO <sub>4</sub> -4%	221	15.5	--	--
	197	13.8	1.55	--
	166	11.6	1.45	--
	284	19.9	0.8	0.4
K <sub>2</sub> SO <sub>4</sub> -2%	265	18.6	1.3	--
	201	14.1	0.75	0.3
Untreated controls	428	30.0	<0.1	--
	498	34.9	<0.1	0.6
	320	22.4	<0.1	--
	446	31.2	<0.1	--
Controls saturated four times w/deionized H <sub>2</sub> O	483	33.8	<0.1	--
	314	22.0	<0.1	0.9
	392	27.4	<0.1	--
	397	27.8	<0.1	--

APPENDIX B

UNCONFINED COMPRESSIVE STRENGTHS, SALT, AND MOISTURE  
CONTENTS OF CORES HUMIDIFIED AT 100% RH FOR 14 DAYS

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
CaCl <sub>2</sub> -8%		None		
CaCl <sub>2</sub> -4%	21	1.5	1.95	4.9
CaCl <sub>2</sub> -2%	104	7.3	0.5	1.6
Ca saturated	275	19.3	<0.1	1.6
	275	19.3	<0.1	1.5
	300	21.0	<0.1	1.5
MgCl <sub>2</sub> -8%	10	0.7	1.8	7.0
MgCl <sub>2</sub> -4%	13	0.9	1.7	6.1
MgCl <sub>2</sub> -2%	29	2.0	0.95	3.3
Mg saturated	253	17.7	<0.1	1.7
	273	19.1	<0.1	1.7
	314	22.0	<0.1	1.7
NaCl-8%	4.5	0.3	1.75	9.6
	4.5	0.3	2.25	10.7
	0	0	2.25	11.8
NaCl-4%	6	0.5	1.75	10.7
	8	0.6	1.25	9.3
	7	0.5	1.65	10.0
NaCl-2%	7	0.5	1.3	9.5
	8	0.6	1.5	9.6

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
Na saturated	170	11.9	<0.1	1.4
	205	14.4	<0.1	1.5
	157	11.0	<0.1	1.4
KCl-8%	13	0.9	2.7	7.1
	11	0.8	2.6	9.6
KCl-4%	14	1.0	1.85	7.6
	14	1.0	2.3	7.2
	21	1.5	1.55	5.5
KCl-2%	22	1.5	1.0	4.4
	25	1.8	1.0	4.0
K saturated	too badly cracked to obtain sample			
Na <sub>2</sub> SO <sub>4</sub> -8%	100	7.0	2.5	3.0
	46	3.2	1.45	4.1
	11	0.8	4.9	6.4
Na <sub>2</sub> SO <sub>4</sub> -4%	37	2.6	2.35	3.6
	43	3.0	1.9	4.2
	132	9.2	1.2	2.0
Na <sub>2</sub> SO <sub>4</sub> -2%	39	2.7	1.75	3.4
	70	4.9	1.6	--
	150	10.5	1.6	2.2
MgSO <sub>4</sub> -8%	63	4.4	1.75	3.3
	102	7.1	1.4	2.7
	83	5.8	1.75	--

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
MgSO <sub>4</sub> -4%	85	6.0	1.6	3.4
	152	10.6	1.0	1.9
	101	7.1	1.5	2.8
MgSO <sub>4</sub> -2%	35	2.5	1.8	3.4
	191	13.4	0.9	2.0
	56	3.9	1.4	2.9
CaSO <sub>4</sub> -8%	220	15.4	8	1.5
	195	13.7	8	1.4
CaSO <sub>4</sub> -4%	270	18.9	4	1.7
	313	21.9	4	1.4
	231	16.2	4	1.5
CaSO <sub>4</sub> -2%	292	20.4	2	1.5
	307	21.5	2	1.5
K <sub>2</sub> SO <sub>4</sub> -8%	89	6.2	1.6	1.4
	109	7.6	1.45	1.0
	162	11.3	1.2	1.3
K <sub>2</sub> SO <sub>4</sub> -4%	157	11.0	1.2	3.4
	122	8.5	1.05	1.9
	115	8.1	1.2	2.8
K <sub>2</sub> SO <sub>4</sub> -2%	127	8.1	0.5	1.4
	136	9.5	0.8	1.1

Treatment	Unconfined compressive strength (psi)	Unconfined compressive strength (kg/cm <sup>2</sup> )	Soluble salt content (% by weight)	Moisture content (% by weight)
Untreated	218	15.3	<0.1	1.4
controls	227	15.9	<0.1	1.3
	202	14.1	<0.1	1.3
Controls	318	22.3	<0.1	1.6
saturated	252	17.6	<0.1	1.8
4 times with	257	18.0	<0.1	1.7
deionized H <sub>2</sub> O	200	14.0	<0.1	1.5

## APPENDIX C

### A DEVICE FOR SULFUR-CAPPING IRREGULAR SOIL CORES

As shown in Fig. 15, a drill press designed to hold a portable drill was modified by linking a horizontal metal plate on top of the drill mount to a similar plate below the mount. A length of aluminum flashing similar to a 90° "angle iron" was glued to the lower plate in a vertical position. After drilling three matching holes in both plates in a triangular pattern, they were joined by bolts held with wing nuts. Soft, thick rubber washers at the three corners allowed the flashing to be adjusted perpendicular to the base of the drill press.

The samples were held firmly in the vertical position, nestled in the flashing by rubber bands. A standard 5.08 cm (2 in) Soil Test capping mold was then placed on the drill press base after filling the oiled cavity with molten sulfur heated to about 138°C. Then the sample end was lowered into the sulfur and held in place until the sulfur hardened (one or two minutes). It was then twisted free of the mold.

To cap the opposite end, the apparatus was disassembled and the lower plate replaced with a smooth plate identical to the upper. The lower plate was adjusted

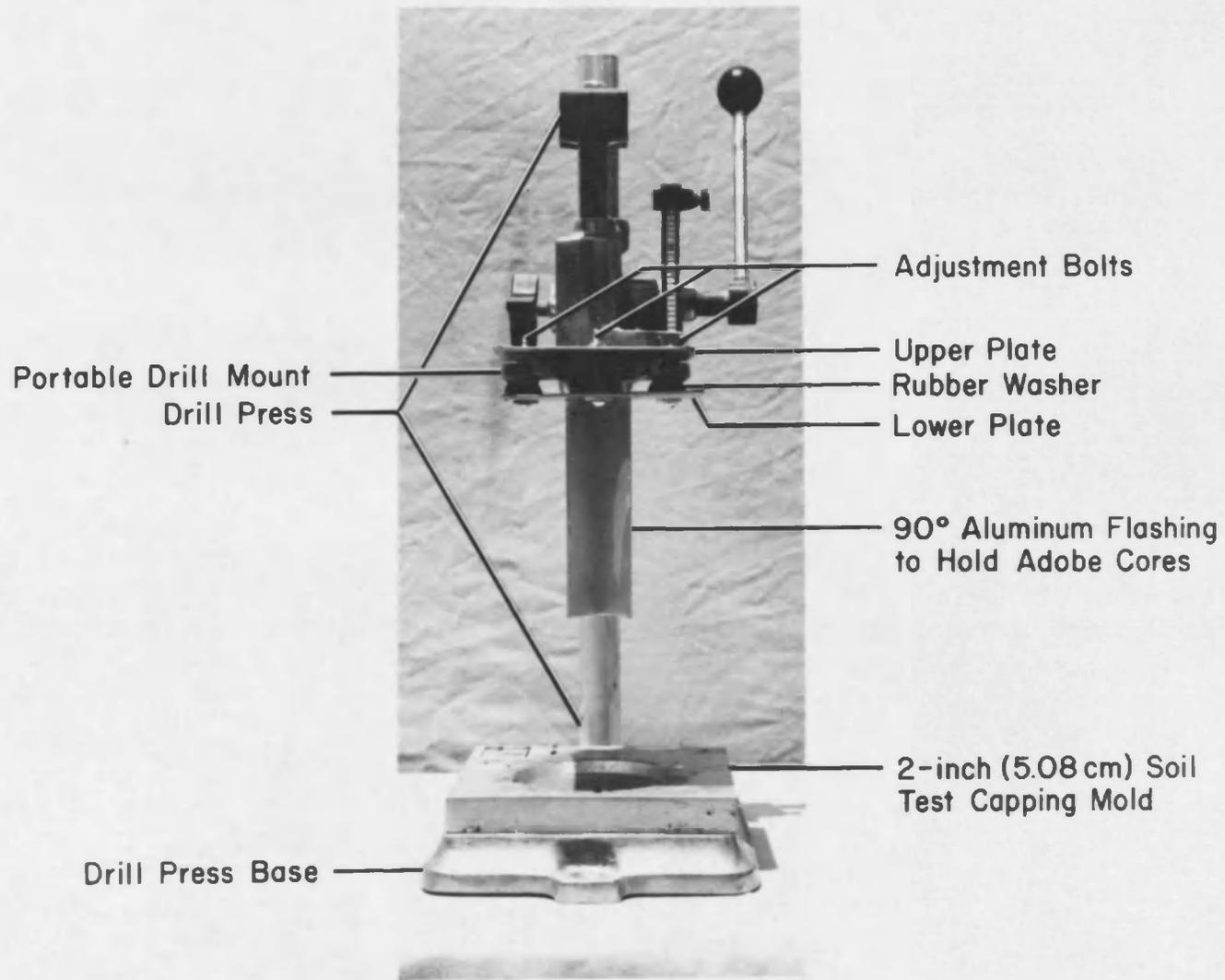


Fig. 15. Device for sulfur-capping adobe cores.

parallel to the drill press base. Petroleum jelly was applied to the capped ends of the samples and they were twisted firmly against the lower plate to obtain a tight seal. Held by the viscosity of the petroleum jelly, the samples' second caps were applied the same as the first ones.

Complete physical protection and extreme caution is advised when undertaking this procedure since molten sulfur could be splashed should the sample become dislodged.

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