A PROGRAM OF INVESTIGATION AND LABORATORY RESEARCH OF ACRYLIC-MODIFIED EARTHEN MORTAR USED AT THREE PREHISTORIC PUEBLOAN SITES

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1
INTRODUCTION

South of the Rockies is the Colorado Plateau, encompassing western Colorado, southeast Utah, northern Arizona, and northwest New Mexico. In its lower elevations it is a formidable, though beautiful, landscape of canyons sliced deeply through colorful sandstone, flat mesas rising abruptly above broad valleys, little fertile soil, and only one perennial river system – the Colorado and its northern tributaries. There are cool, moist mountains with pine and fir forests and upland with mixed stands of juniper and pinyon. Patches of grass and scrub brush dot the lower mesas. Most of the province has a long, dry, warm summer broken by localized thunderstorms that tear at the thin soil. Winters are cold with considerable snow. Even with so many apparent drawbacks, the Plateau offered suitable habitat for a dense, aboriginal farming population. In some parts of the region these folk adapted and survived in greater numbers than anywhere else in the Southwest.[1]

1.1 Investigation Rational

Echoes of these aboriginal farmers still reverberate in special places of the Colorado Plateau, on the mesas and in the canyons, where sandstone settlements remain in mute tribute to their builders.

The National Park Service is responsible for managing many of the site remains of Pre-Columbian culture in the Southwestern United States. There are 29 national parks, monuments and sites on the Colorado Plateau, in the four-corners region of Colorado, Utah, Arizona, and New Mexico. A land of geological and climatic contrasts, this corner of the present United States has been home to humans for at least 12,000 years.[2]

By 500 B.C. soil-based agriculture, particularly maize farming, had become firmly established in this geographic region. Even though hunting still played a major part in the survival of the people living here, agriculture fundamentally changed their culture. The future became

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1 Florence C. Lister and Robert H. Lister, *Those Who Came Before* (Globe, Arizona: Southwest Parks and Monuments Association, 1983), 14.

2 David Grant Noble, *Ancient Ruins of the Southwest* (Flagstaff, Arizona: Northland Publishing, 1991), ix.

important; stability was required to plant and tend crops and plan for harvests. Corollary technologies of shelter building using brush and earth, and container making began to take on a new importance. By A.D. 500 the fundamentals of what is now called the Southwest Tradition were firmly established. Archaeologists separate the members of the Southwest Tradition into three large culture groups, and several smaller ones, all sharing ancestral roots but with distinct traditions. The three large groups are the Mogollon, the Hohokam and the Anasazi.

These groups reached their apogee in the period of A.D. 1000-1200. By A.D. 1450 they were in serious decline. Of the three, the best known, and perhaps the most misunderstood, is the culture known as the Anasazi. When they abandoned their settlements on the Colorado Plateau in the 13th century, they left a spectacular physical legacy, hundreds of cliff dwellings and surface pueblos, primarily made of sandstone masonry laid with earthen mortar. Three of these Anasazi sites are central to this research.

The Anasazi lived in a land of sandstone and earth, and their structures reflect these materials. Wood, precious as fuel, was used to support floors and roofs, and as lintels. Early in their settlement of the plateau, their homes were modest, pit houses or other wood and earth shelters. Later architecture, the concern of this study, was principally stone masonry with earthen mortar. The Anasazi used mortar for the same reasons masons have always used mortar. It provides a leveling agent for bedding stones, and unites individual masonry units, transferring and distributing loads. Mortar also blocks the weather and prevents the infiltration of water and animals. The more regular the masonry stones, achieved either through shaping or by taking advantage of natural beds or joints, the less water and earth was required to make mortar to fill the gaps between the stones.

Earthen mortar had at least three advantages for these early builders: it was plentiful; it required little extra labor to prepare; and, when maintained or protected, it was durable and effective in the Southwestern climate. At sheltered sites, original earthen mortar has remained in good condition almost 800 years after its installation. But in areas subject to moisture or earth movement,

such as subterranean ground moisture in kivas and direct exposure to snow and rain in unprotected sites, earthen mortars can and have failed. It is the National Park Service's responsibility to maintain these sites, and often that means repairing or stabilizing original masonry, and in many areas maintaining sections reconstructed or stabilized after archaeological excavation.

It is important to remember that the structures at most Southwestern Anasazi sites are incomplete. Gone are the roofs which shed water and kept damaging moisture from the walls and interior mud plasters. And gone, too, are the exterior plasters that archeologists believe must have covered much of the Anasazi masonry.[3] The sites are now fragments of architecture exposed to weather, without caring inhabitants to make repairs.

Figure 1. Abandonment and the inexorable forces of nature, particularly water and wind, have reduced the Anasazi pueblos to ruins. Pueblo Bonito at Chaco Culture National Historical Park is an example of such a ruin, fully exposed to the weather. The National Park Service is the modern day custodian of these sites, responsible for preserving and maintaining 29 national parks, monuments and sites in the area of the Colorado Plateau. Amended earthen mortar is one of the tools used by maintenance crews to repair the sandstone walls.

The National Park Service distinguishes between intrinsic and extrinsic stabilization. Intrinsically stabilized sites are those with a high degree of material integrity, valuable for their con-

3 Stephen H. Lekson, *Great Pueblo Architecture of Chaco Canyon, New Mexico* (Albuquerque: University of New Mexico Press, 1984), 29.

tribution to continuing research and/or interpretive potential, and the heaviest burden of preserving the site is placed on the visitor, who is asked to respect the fragile authenticity of such sites. Only critically needed physical stabilization is performed at these locations. Extrinsically stabilized sites have been more heavily modified, and the sites, modified with amended mortars, internal reinforcement, paved trails and paths, etc., bear the burden of preservation.[4]

In an effort to make more lasting repairs, the National Park Service has used alternative, or modified, mortars since the earliest campaigns of stabilization in the late nineteenth century. Many pueblo ruins and other architectural remains have been repaired with Portland cement mortars, a material now recognized as being physically incompatible with the original masonry system. Placed in contact with the softer and more porous and permeable sandstone, cement invariably causes decay of the softer stone if moisture is present. Water, unable to exit the masonry through more permeable mortar, saturates the stone, often carrying soluble salts from the adjacent cement. Over time, freezing temperatures, salt crystal formation and dissolution of internal cementing agents cause the stone face to deteriorate. Portland cement mortars are difficult to repair, requiring invasive methods of removal for periodic repointing. However, at some ruins where direct visitor contact occurs, cement mortar stabilization must be used to keep the ruins standing.[5]

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4 Todd R. Metzger, *Ruins Stabilization Report, Technical Series No. 53, Ruins Stabilization: A Handbook* (Denver: National Park Service, Rocky Mountain Region, 1988), 12-15.

5 Sun Temple at Mesa Verde is such a site. An exposed mesa top ruin on Ruins Road on Chapin Mesa, Sun Temple is visited, and walked on, by thousands of people each year.

Mortars made of Portland cement and sand should not be confused with soil-cements, where cement is a minor (usually 10% or less) component of a basically earthen mortar. Soil-cements have been used successfully as mortars in some sandstone ruins and as amended adobe bricks to repair adobe ruins. Efflorescence can be a problem with soil-cement mortars, and soil-cement adobes are not always compatible with weaker historic adobes. The gray or white color of cements can complicate the job of obtaining a compatibly-colored soil-cement mortar or modified adobe.

Figure 2. These sandstone masonry blocks at Aztec Ruins National Monument are eroding at a faster than normal rate because of the adjacent Portland cement-based mortar. The deleterious effects of cementious mortars are one reason the National Park Service has shifted to more compatible acrylic emulsion-based earthen mortars at some ruins sites in the Southwest. (A quarter is shown for scale.)

Asphalt-based soil stabilizers, such as bitumen, also were used at some ruins sites, and much of the asphalt-amended mortar is still in place. A durable amendment still used as a commercial adobe stabilizer, it has the disadvantage of darkening the mortar, and is no longer used at National Park Service sites on the Colorado Plateau.

Since the mid-1970s aqueous polymer emulsions, particularly acrylic and vinyl emulsions, have been used as earthen mortar amendments to increase soil particle adhesion, rendering the repair mortar more durable and more resistant to water erosion, thereby lengthening the maintenance cycle. These amendments are usually colorless when dry, facilitating the task of making compatibly-colored repair mortars.

Inorganic binders, such as cements or lime, are essentially mineral, and not subject to degradation by light and oxygen, as organic, polymer, consolidants are. Organic binders, however, can confer some valuable properties, such as resilience and flexibility not delivered by inorganics.[6]

Recently the National Park Service has begun an initiative to call attention to the deteriorating condition and increased maintenance needs of the ruins in its care. In a June, 1995, draft report titled *Vanishing Treasures: A Legacy in Ruins*, the Park Service's mission statement is introduced:

> Unique and perishable masonry ruins important to our national heritage are deteriorating at an increasingly rapid rate. The National Park Service can successfully fulfill its mandate to manage and preserve these resources for future generations through the development and implementation of a long-term ruins preservation program.
>
> A National Park Service ruins preservation program is essential to provide a last defense against the loss of these tangible symbols of American's heritage. An effective program can preserve the integrity, information and special meaning that these places hold for this and future generations.[7]

This research project, the investigation of the performance of a specific acrylic emulsion soil amendment, meshes well with the National Park Service goal of responsible and effective ruins management. The Conservation Program in the Intermountain Cultural Resources Center of the National Park Service has initiated a multi-year effort to better understand the behavior of all amendments used in mortars throughout the Colorado Plateau and the Desert Southwest parks. This research into the properties of Rhoplex E-330, an acrylic dispersion, is a pilot effort in this work.

Earthen architecture can survive for hundreds of years in dry climates, but begins to weather when subjected to moisture, whether from rain, condensation, high humidity or rising ground water. The rate of weathering depends on environmental conditions, of course, but also on the characteristics of the earthen material, including mineralogical composition, particle distribution,

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6 Morgan W. Phillips, "Consolidation of Porous Materials: Problems and Possibilities of Acrylic Resin Techniques", *Technology & Conservation* 4, no. 4 (1979): 42.

7 *Vanishing Treasures: A Legacy in Ruins, In-house Draft* (Washington, DC: National Park Service, 1995), 2.

porosity and soluble salt content. Major weathering processes include the breakdown of the silt-clay matrix, salt crystallization, and dimensional changes caused by cycles of wetting and drying, and freezing and thawing.[8]

Acrylic emulsion amendments provide a more durable mortar with little change in visual appearance, and without danger to sandstone masonry risked when a hard, impermeable material such as Portland cement is added. However the perfect soil amendment still has not been found, and the National Park Service has observed some failures of the acrylic-modified earthen mortar, resulting in premature disintegration, for reasons that are not entirely clear. Some possible explanations are reduced permeability caused by the polymer, freeze/thaw damage, dimensional instability due to water, incorrect application or usage, and incomplete polymer film formation caused by rapid drying, or drying below 50°F.

Although field tests have been conducted using acrylic emulsions and there is abundant anecdotal evidence about its performance, little laboratory work has been undertaken to help understand the interaction between the polymer and the specific soils used. This research project attempts to examine and evaluate some of the important variables involved in the use of acrylic emulsion-amended earthen mortars in a controlled laboratory situation and identify certain predictors of success and failure in the field. It builds on fundamental work by Dennis Fenn, formerly of the National Park Service. Fenn, working with others in the National Park Service, introduced the idea of using a polymer-based mortar additive approximately 20 years ago. As a result of this work, the use of E-330 and similar polymer emulsions has grown significantly within the National Park Service and other natural and cultural resource agencies in the last 20 years. (Early experiments with E-330 are discussed in section 2.2.1.)

8 Paul W. Brown, Carl R. Robbins and James R. Clifton, "Adobe II: Factors Affecting the Durability of Adobe Structures", *Studies in Conservation* 24 (1979): 23.

The Conservation Program of the Intermountain Cultural Resources Center and the University of Pennsylvania Architectural Conservation Laboratory were partners in this research through a cooperative agreement. They selected three sites for study: Mesa Verde National Park, in Colorado, and Aztec Ruins National Monument and Chaco Culture National Historical Park, both in New Mexico. All are Anasazi sites where acrylic emulsion, Rhoplex E-330, has been used since the late 1970s or the early 1980s.

Three techniques were used to gain information about the use and performance of amended mortars at the test sites: a search of available literature, including the work by Fenn; interviews with the stabilization crews at the selected sites to learn about success and failure in the field, and about current practices; and laboratory soil analysis and performance testing of manufactured acrylic-modified mortar samples.

A trip was made to the three sites in October, 1994, to interview the maintenance supervisors or stabilization archaeologists about practices, experiences, and successes and failures, and to collect samples of soil for laboratory tests.

1.2 The Sites

Mesa Verde National Park is located on a large mesa in the southwest corner of Colorado, near the modern town of Cortez. One of the most important centers of Anasazi culture, the cliff dwellings and surface pueblos on the mesa were once home to approximately 2,500 people. The stabilization crew at Mesa Verde maintains the stabilized ruins at Mesa Verde, and also performs stabilization and repair work at Anasazi pueblos in Hovenweep National Monument, which sits astride the Colorado-Utah border west of Cortez, and Chimney Rock Archaeological Area which contains the ruins of a Chacoan outlier, east of Mesa Verde. Neither Chimney Rock, which is under the jurisdiction of the U. S. Forest Service, nor Hovenweep have a full-time stabilization crew.

Chaco Canyon lies several miles off a state highway south of Bloomfield, New Mexico, in an arid part of the state. There, on either side of Chaco Wash, in the valley and on the surrounding plateaus, are the ruins of hundreds of Anasazi pueblos, remnants of the most important center of Anasazi culture.

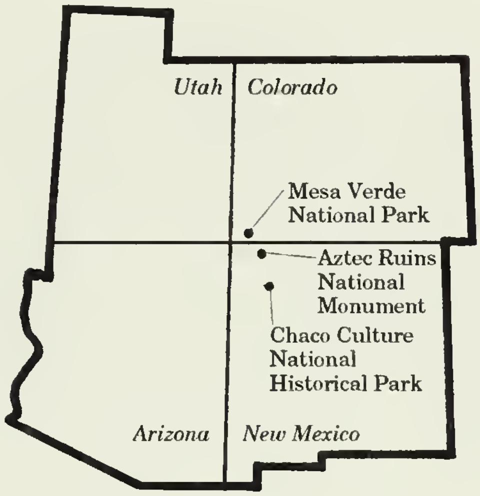

Figure 3

In 1980 the name of the park was changed from Chaco Canyon National Monument to Chaco Culture National Historical Park, putting emphasis in the name on the culture of the people who built the settlements, and whose influence extended far beyond the confines of the canyon cut by Chaco Wash. In this report, Chaco Canyon refers to the park and specifically to the physical location of the ruins important to this research.

Aztec Ruins National Monument is on the edge of small New Mexico town also named Aztec, in the northwest corner of the state, on a line between Mesa Verde and Chaco Canyon. Nearby, the Animas River, bordered by cottonwood trees, separates the ancient pueblo from the modern town. Much smaller than either Mesa Verde or Chaco Canyon, Aztec Ruins displays architectural evidence of having been influenced by builders from both the larger sites.

2
MATERIALS

2.1 Soils

Sixteen soils from Mesa Verde, Chaco Canyon, Aztec Ruins and related sites were collected by the researcher or by staff at the National Park Service sites and shipped to Philadelphia for characterization and testing. A seventeenth soil, a commercial adobe soil from near Santa Fe, New Mexico, was added to the test as a control. Only the soils currently being used for repairs – Mesa Verde Blend, Chaco Canyon BLM Quarry, and Aztec Ruins Blend – and New Mexico Alcalde Adobe were used in the second part of this project, testing earthen mortars.

In most cases the sources of the soil for original mortars are not precisely known, although the sources are presumed to be reasonably close to the construction sites because the builders would not have wanted to carry soil for earthen mortar any farther than necessary. Soil for decorative plasters is another concern; texture, color, and shrinkage characteristics might have demanded special acquisition efforts.

Since all three sites are in national preserves, the stabilization crews are restricted from excavating soils for mortar repairs within park and monument boundaries. This is considered mining, an activity not normally permitted. Soils must be obtained from alternate sources, and these soils may or may not match the original soils used by the builders, in terms of mineralogy, grain size distribution, or color.

Color and texture are important considerations for modern day maintenance crews, who try to make their repairs visually compatible with historic material. The task of finding compatible mortars is made more complicated when soils must be blended to achieve suitable color or texture. Particle size distribution is important when trying to achieve a suitable match to the texture of

surrounding materials. Mortars which contain more or less sand can present perceptibly different appearances. An advantage of Rhoplex E-330, and some other polymeric materials, is their colorlessness when dry. Their addition results in little color change to soil blends.

Mesa Verde repair material is a composite of two soils, a red loess obtained from the mesa tops within the park called "Mesa Verde Red", and yellow "crusher fines" obtained from the Ute Mountain Indian Reservation on the south edge of the National Park, called "Mesa Verde Yellow". The loess is not mined but simply shoveled from the surface of the mesa. Loess soils are very fine silts or clays originating in arid regions, and transported by wind.[9] (*Table 1* lists all the soils characterized for this project, and their site origin.) The proportions of red to yellow soil varies depending on where repairs are being made. On the mesa top, historic mortars are much redder. There, primarily red loess is used in the soil blend for mortar repairs. At the cliff dwellings, the historic mortars are more yellow, so the proportion of yellow soil in the repair blend increases. For the purposes of this study, a "typical" Mesa Verde soil mix of 2:1, red to yellow, was used, named "Mesa Verde Blend".

Besides the red and yellow soils from Mesa Verde, four other soils from the Mesa Verde area were brought back to Philadelphia for characterization. These include two loess soils from Hovenweep National Monument, "Hovenweep Pink" and "Hovenweep Red", and two soils from road cuts at Chimney Rock Archaeological Area, "Chimney Rock Lower" and "Chimney Rock Middle". All four soils have been used for mortar repairs in the past.

Chaco Canyon stabilization crews currently obtain repair material from a BLM quarry north of the park. Other soils have been used in the past, and some of these might be available for use again if it seems that they would provide a more durable mortar repair.

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9 Mary O. Griffitts, *Guide to the Geology of Mesa Verde National Park* (CO: Mesa Verde Museum Association, 1990), 84.

In addition to the BLM quarry soil, four other soils from Chaco Canyon were characterized. They include: soil used by Fenn in the test walls at Chaco, "South Gap"; another soil that has been successfully used for repairs in the past, "Tsin Kletsin"; mortar soil from a wall fall (possibly original material), "Chetro Ketl Prehistoric"; and soil from an area thought to be a potential site of historic soil mining, possibly for building materials, "Chetro Ketl Field".

The Aztec Ruins maintenance crew uses a special blend of three soils obtained from external sources – a sand, a silt and a clay – in the ratio of 6:2:3. This soil, "Aztec Blend", was designed to approximate the color and texture of original mortar found at Aztec Ruins, and provide a workable and lasting repair.

A seventeenth soil, a commercial adobe soil from near Santa Fe, New Mexico, "New Mexico Alcalde Adobe", was added to the test as a control, a soil known to work well in earthen construction. At least, that was the original assumption. Tests showed that the soil is almost all sand (approximately 85%), normally not a recipe for a good adobe soil. But in retrospect it was fortunate that the soil was included, because it provided a contrast to some of the high clay and silt soils in the test program, and ultimately provided some valuable insights to the performance of Rhoplex E-330 in high sand soil.

SOILS CHARACTERIZED FOR THIS RESEARCH

Soil Name*	Abbreviation	National Park Service Jurisdiction	Tested as Amended Mortar
Mesa Verde Red	MEVE RED	Mesa Verde	
Mesa Verde Yellow	MEVE YEL	Mesa Verde	
Mesa Verde Blend	MEVE BL1	Mesa Verde	yes
Hovenweep Red	HVWP RED	Mesa Verde	
Hovenweep Pink	HVWP PNK	Mesa Verde	
Lower Chimney Rock	CMRK LOW	Mesa Verde	
Middle Chimney Rock	CMRK MID	Mesa Verde	
Aztec Ruins Sand	AZTC SND	Aztec Ruins	
Aztec Ruins Silt	AZTC SLT	Aztec Ruins	
Aztec Ruins Clay	AZTC CLY	Aztec Ruins	
Aztec Ruins Blend	AZTC BL1	Aztec Ruins	yes
Chaco Canyon BLM Quarry	CHCN QRY	Chaco Canyon	yes
Chaco Canyon South Gap	CHCN SOU	Chaco Canyon	
Chaco Canyon Chetro Ketl Field	CHCN CKF	Chaco Canyon	
Chaco Canyon Chetro Ketl Prehistoric	CHCN PRE	Chaco Canyon	
Chaco Canyon Tsin Kletsin	CHCN TKN	Chaco Canyon	
New Mexico Alcalde Adobe	NMEX ALC	None	yes

*An unofficial name given to each soil based on geographical location, color, or other unique characteristics.

Table 1

2.2 Rhoplex E-330 Amendment

Portland cement is one of the most widely used construction materials in the world. Mixed with aggregate to form concrete it has many virtues. Concrete is very strong in compression. It can be molded into almost any shape, often at the construction site. It is relatively unaffected by water, unlike other construction materials such as wood and most metals. And compared to those materials, it is often less expensive for large projects.

However, concrete is not a perfect material. Compared to the alternative of steel, and sometimes wood, it is lower in tensile strength and ductility, and has a lower strength-to-weight ratio. For some applications, for example roads and bridges subjected to deicing chemicals, it has greater than desired permeability.

Adding latex emulsions to Portland cement mixes was an early attempt to modify and improve this brittle material, to make it more resilient and less permeable. The first patent for latex (in this case natural rubber) for use in concrete was granted to Cresson in England in 1923. After World War II, the synthetic latex industry boomed, and since the 1960s various polymer emulsions have been added to Portland cement and aggregate to make polymer (latex) modified concrete and mortar.[10] These emulsions include styrene-butadiene rubber, polyvinyl acetate, polyvinyl chloride and polyacrylics.

Natural rubber is a latex, and so are modern polymers made by the emulsion polymerization process, where the polymerization is carried out in a water medium containing an emulsifier (soap) and a water-soluble initiator. Because the reaction takes place in a large volume of water, it is easy to control the reaction temperature and conditions.[11] The polymer particles formed are very small, often on the order of 0.05 to 0.15 μm, stabilized by soap. The resulting latices are usually raw materials for further processing, being turned into commercial products such as white glue or latex paints, by formulation with thickeners, pigments, etc. Their film-forming and adhesive qualities make them especially valuable.[12]

The Rhoplex® E-330 Cement Mortar Modifier for these tests was obtained from the manufacturer, Rohm and Haas of Philadelphia. Rhoplex E-330 was chosen for four reasons: 1) it is the same material used by Dennis Fenn in his experiments at Chaco Canyon; 2) it is a high quality polymer made by one of the foremost manufacturers of acrylic materials; 3) it is in current use by the National Park Service at several Southwestern sites; and 4) it is formulated for use as an amendment. Normally sold in 55-gallon drums, a smaller amount was made available for these tests. According to Rohm and Haas literature, E-330 is a water dispersion of an acrylic polymer

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10 V. Ramakrishnan, *Synthesis of Highway Practice 179: Latex-Modified Concretes and Mortars* (Washington: Transportation Research Board, National Research Council, 1992), 3.

11 Michael L. Berins, ed., *SPI Plastics Engineering Handbook* (New York: Van Nostrand Reinhold, 1991), 36-7.

12 Stephen L. Rosen, *Fundamental Principles of Polymeric Materials* (New York: John Wiley & Sons, 1982), 184-5.

specifically designed for modifying Portland cement compositions. Its uses include patching and resurfacing, floor underlayments, precast architectural building panels, stucco, terrazzo flooring, industrial cement floors, and highway and bridge deck repair. Compared with unmodified cement mortars, polymer-modified mortars have superior flexural, adhesive, and impact strengths, as well as excellent abrasion resistance. E-330-modified cement mortars have excellent adhesion to a variety of surfaces, such as concrete, masonry, brick, wood and metals.[13] In cement, Rhoplex E-330 also decreases permeability.[14] Water-based acrylic polymer concrete amendments, such as Rhoplex E-330, have been used commercially for approximately 35 years.[15]

Rhoplex E-330 is a copolymer, a combination of methyl methacrylate and ethyl acrylate, dispersed in an aqueous medium. Created by a process of emulsion polymerization, the resulting product consists of a proprietary blend of the two monomers with other minor constituents, with a small particle size, ≤ 1.0 µm. These particles are so small that Brownian forces keep them in suspension. Unlike polymers dissolved in solvents (true solutions) polymer emulsions can support high concentrations of polymers of high molecular weight (up to approximately 70% solids) without becoming unworkably viscous.[16]

Rhoplex E-330 is a milky white liquid containing approximately 47% solids by weight, in an alkaline water base. It has a pH of 9.5 - 10.5, a specific gravity of 1.0 - 1.2, and freezing and boiling points the same as water. The emulsion is stable in storage from 34°F to 120°F, and stable through five cycles of freezing and thawing. Dried, the polymer is stable to 350°F, the onset of polymer decomposition.[17]

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13 *Rohm and Haas Cement Modifiers*, (Philadelphia: Rohm and Haas, March 1993).

14 Joseph A. Lavelle, *Acrylic Latex Modified Portland Cement*, Presented at the American Concrete Institute 1986 Fall Convention, Baltimore, MD, 11, 18.

15 Lavelle, *Acrylic Latex Modified Portland Cement*, i.

16 Donald Glusker, Research Associate for the Museum Applied Science Center for Archaeology, interview by author, 20 January 1995, University Museum, University of Pennsylvania, Philadelphia.

17 *Material Safety Data Sheet, Rhoplex E-330 Emulsion* (Philadelphia: Rohm and Haas, 11 July 1990), and *Rohm and Haas Cement Modifiers*, 1993.

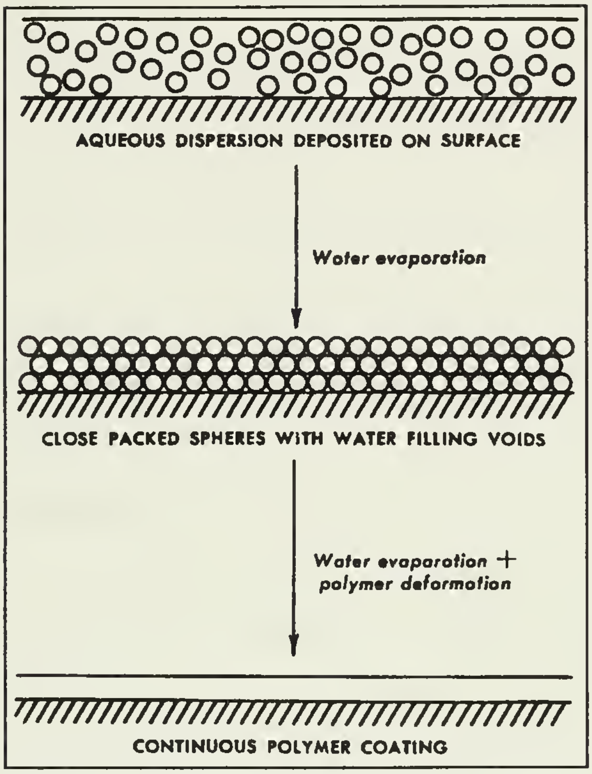

Figure 4. Rhoplex E-330 film formation occurs as a result of water evaporation and polymer deformation. No chemical change is involved. (From Lavelle, 1986)

Acrylic emulsions work by coalescent film formation, and are often used as adhesives. As the water evaporates, the polymers coalesce into a tough film. No chemical reaction takes place; no curing is necessary. Unlike cements or lime which continue to change chemically days or weeks after installation, or some monomeric or polymeric consolidants which polymerize or cross-link *in situ,* E-330 simply dries out and forms a film. And as soon as it dries, the film is as strong and durable as it will ever be. In the case of E-330 the resulting film is not soluble in water, although it swells and softens slightly when wet.[18] It is presumed that the material works as a soil amendment by acting as an adhesive between the soil particles.

Rohm and Haas makes many different products under the Rhoplex trademark for many different uses, but none of the uses are as amendments to soil. E-330 is a cement mortar amendment developed for and used by the construction industry. It is important to note that Rohm and Haas has always been responsive to requests for help and information when queried by the National Park Service, but they have not studied the material as an amendment for soil, nor have they generated

[18] Robert Falconio, Rohm and Haas Customer Representative, Construction Products Division, telephone interview by author, 21 March 1995, Philadelphia.

test data about its performance in soil systems. One of the goals of this research is to provide greater insight into the performance of this polymer emulsion with earthen materials for conservation use.

Rhoplex E-330 has several attractive qualities that make it a good candidate for use as an earthen mortar amendment. In bulk form it is stable at temperatures between the freezing and boiling points of water, although it should be used at temperatures above 50°F. It is water-based, so the issues of volatile solvent evaporation are avoided, and it is compatible with traditional water-based mortars. It is easy to use (simply mixed with water), non-flammable, and non-toxic.[19] Like other acrylics, and unlike many other polymers, it is transparent to, and relatively unaffected by, ultraviolet light.

Thermoplastic polymers – including waxes, acrylics, rubber and other polymers that soften with heat – possess a unique glass transition temperature (T_g) above which the materials soften, or become less glass-like and more plastic. Emulsions of thermoplastic materials also have a T_g, and it impacts the performance of the materials in two ways, one as the film is formed, and another after film formation. When the polymer emulsion drys at a temperature below the T_g, film formation itself is inhibited. After the polymer has coalesced into a film, the film is flexible above the T_g, but becomes brittle when cooled below the glass transition temperature.[20] Rhoplex E-330 has a T_g of approximately 50°F.

19 *Material Safety Data Sheet, Rhoplex E-330 Emulsion* , 1990.
20 Interview with Donald Glusker.

2.2.1 History of Early Rhoplex Use

From the July, 1932, issue of *The Masterkey*, the journal of the Southwest Museum, Los Angeles:

> Wanted, by the National Park Service of the Department of the Interior, a clear, transparent, waterproof solution that when sprayed on prehistoric masonry will preserve it from weathering without obscuring it from view....One of the vexing problems that faces the Service in its administration of the national monuments, particularly in the Southwest, is the preservation of the walls of the prehistoric cliff-dweller and other pueblo ruins which many of them contain. Some of the ruined dwellings were built of earth, others of stone laid up with earth mortar....The ideal solution of the problem would be the preparation of a clear, transparent, waterproof coating which could be sprayed on the walls, thus making them waterproof and still leaving the masonry open to inspection by the many thousands of people who are visiting the monuments each year.[21]

The history of the use of Rhoplex E-330 as a consolidant for earthen materials or as a soil amendment began in the early 1970s, although as the above quote above demonstrates, the National Park Service has sought chemical means of ameliorating masonry deterioration for more than 60 years. Darrel J. Butterbaugh, scientist and retired manager from Rohm and Haas, volunteered as a Research Associate with the Museum Applied Science Center for Archaeology (MASCA) at the University Museum of the University of Pennsylvania, Philadelphia, in 1971. Vacationing in Arizona, Butterbaugh visited Casa Grande Ruins National Monument, the Hohokam ruin from A.D. 1100, made of puddled adobe and protected by an effective but perennially controversial metal shelter. Challenged to find a way to protect earthen architecture without shelters, Butterbaugh, through MASCA, began a series of experiments that introduced a new chemical weapon in the continuing fight against adobe deterioration.

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21 "Park Service Wants a Clear, Waterproof Solution for Ruins" *The Masterkey* 6, no. 3 (1932): 77.

The following summary lists the significant dates and events in the early use of Rhoplex E-330 as an amendment, or consolidant, of earthen materials. The details of the summarized events are included in this section.

SUMMARY OF EARLY RHOPLEX E-330 USE

Date	Event
1972	• Darrel Butterbaugh, a researcher at MASCA, began testing Rhoplex emulsions as applied coatings on adobe (and stone) at the University Museum, University of Pennsylvania, in Philadelphia.
Summer 1973	• Butterbaugh conducted field tests of acrylic emulsions and acrylic solutions as spray-applied coatings at Chaco Canyon and Pecos National Historical Park, and submitted a report to MASCA.
1974	• James Kriegh and Hassan Sultan of the University of Arizona College of Engineering published a report containing the results of their 1973-74 laboratory experiments with chemical treatments of adobe. They tested 20 combinations of chemicals, including Rhoplex E-330 (acquired from Chaco Canyon), as applied coatings to adobe cubes.
Summer 1975	• Butterbaugh placed two E-330-amended adobe bricks on the roof of the University Museum in Philadelphia.
Summer 1975	• Dennis Fenn, National Park Service, began a test program at Chaco Canyon, at a pueblo site on Chaco Wash, using three polymer products, including Rhoplex E-330, as amendments to earthen mortar.
Fall 1975	• Butterbaugh and Vincent Pigott tested acrylic emulsions as amendments to earthen plasters and adobe bricks at an archaeological site at Hasanlu, Iran. They suggested using acrylic-modified adobes as wall capping to slow earthen wall erosion.

- Fall 1975 • Fenn expanded his Chaco Canyon tests with amended mortars at a site known as Lizard House. Here, he also made some amended-adobe bricks, and left them to weather on the ground. Also at this time, he tested some of the chemicals, including E-330, as spray-applied consolidants to selected horizontal and vertical earthen surfaces of a pit house near Fajada Butte.
- Spring 1976 • Butterbaugh and Pigott tested E-330-amended earth on a prototype of a seismic-resistant wall in Chimaltenango, Guatemala.
- Summer 1976 • Fenn began construction of sandstone test walls near the visitor center at Chaco Canyon. He tested 17 chemicals, including Rhoplex E-330, as amendments to earthen mortar in the test walls.
- Summer 1977 • The test walls at Chaco were extended, and Fenn added additional chemicals to the test. He also left a set of amended adobe bricks on the ground to weather.
- 1978 • Fenn and John Deck issued the final report of the Chaco Canyon research, and listed 10 recommendations for the use of chemical amendments to soil. They identified Rhoplex E-330 as the amendment of choice for earthen mortars, although it was not the only polymer to perform satisfactorily.
- 1979 • Fenn revisited the Chaco Canyon test sites, and reported no surprises. E-330-amended mortars were still holding up well. In addition, he described work at Bent's Old Fort in Colorado, and reported that some amended earthen plasters (including plaster amended with E-330) were holding up well after three years of weather exposure.

All authorities on earthen architecture agree on the effectiveness of shelters as a way to retard the weathering of earthen materials. But agreement ends there, and shelters remain a solution of last resort. Besides the fact that shelters almost always have a jarring visual appearance, many important ruins are simply too large to shelter economically. Besides Casa Grande, some important

and early pit dwellings at Mesa Verde have been sheltered, and while deterioration has not stopped, it has slowed significantly.

Butterbaugh asked his contacts at Rohm and Haas to suggest chemicals that might be suitable for protecting earthen materials. Acrylics quickly became the focus of the search because of their relatively high durability in outdoor environments. After testing many products, Butterbaugh selected two for primary testing: Acryloid A-21, methyl methacrylate as a solution in toluene, and some acrylic dispersions in the Rhoplex family, including Rhoplex E-330.

In 1973 Butterbaugh filed his first field report with MASCA detailing his experiments in the summer of 1973 with acrylics at Chaco Canyon and Pecos National Historical Park, also in New Mexico.[22] At Chaco a freshly excavated pit house was picked as the site for tests. Eight panels, approximately 25-50 square feet often including sections of floor, bench and rim, were sprayed with polymer, including diluted Rhoplex E-863, E-330 and E-826. In some cases, a coat of silicon-based water repellent in mineral spirits was sprayed over the Rhoplex-treated sections. Also at Chaco Canyon, some soft Chaco sandstone was treated with a Rhoplex spray.

At Pecos, the remaining adobe walls of a 16' x 16' room were treated with a diluted spray of Rhoplex E-826, an ultra-fine particle size emulsion, and E-330, sometimes with an overcoat of the water repellent. Butterbaugh reported that some of the adobe bricks at Pecos had a dark, "oily", appearance and did not accept the sprayed emulsion as readily as did the soil at Chaco Canyon. An unpointed wall was pointed with amended mud made with Rhoplex E-863 (a small particle size emulsion made especially for deep penetration of leather) and amended adobe bricks were made with E-330 and E-863.

22 Darrel J. Butterbaugh, "Mud Brick Conservation Project - Field Report", 9 August 1973, Museum Applied Science Center for Archaeology, University Museum, University of Pennsylvania, Philadelphia.

Unfortunately, there was no follow-up of either of these pioneering efforts with the Rhoplex emulsions, and in an October, 1995, conversation Butterbaugh said that he was unaware of the ultimate fate of these early tests.[23]

His experiments with acrylics, sometimes in combination with silicon compounds, continued through the 1970s. In 1972, prior to the test walls at Chaco Canyon and Pecos, he placed 10 adobe clods treated with spray-applied coatings of E-330, E-863, and a silicon-based water repellent on the roof of the University Museum in Philadelphia, a city with a decidedly adobe-unfriendly climate. Typical Philadelphia weather features an average of over 41" of precipitation (including 21" of snow) annually, measurable precipitation (more than .01") an average of 117 days annually, high humidity in the summer and a winter climate that frequently cycles above and below freezing. The average high and low daily temperatures for December, January and February are above and below freezing, respectively.[24] After a year of exposure, only the samples treated with E-330 had survived the test.[25]

In October, 1975, Butterbaugh and Vincent Pigott, Research Specialist with MASCA, completed a series of field tests at Hasanlu in Iran. A total of approximately 140 square meters of mud brick wall were treated in 16 tests. Four types of tests were conducted: first, mud brick walls were soaked with a toluene/polymer solution (B-67 or A-21); second, mud, straw and water plasters were applied to walls, some treated with polymer and some not; third, a mud plaster made with an emulsion polymer (E-330) was applied to treated and untreated walls; and fourth, E-330 emulsion-modified mud bricks were used to build two small test walls.[26]

Two years of observations followed the initiation of the tests at Hasanlu. Butterbaugh and Pigott wrote in their 1978 report that emulsion plasters on untreated walls were not satisfactory; they

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23 Darrel J. Butterbaugh, interview by author, 31 October 1995, Lansdale, Pennsylvania.

24 Frank E. Blair, ed., *The Weather Almanac* (Detroit: Gale Research, 1992), 724-727.

25 Darrell J. Butterbaugh, "Mud Brick Conservation Project - Interim Report No. 2", 14 November 1973, Museum Applied Science Center for Archaeology, University Museum, University of Pennsylvania, Philadelphia.

26 Vincent Pigott and Darrel J. Butterbaugh, "A Programme in Experimental Mudbrick Preservation at Hasanlu Tepe", *Iran* 16 (1978): 162.

failed to adhere to the earthen walls. They believed, though, that an amended plaster over a polymer-treated wall was a satisfactory solution. They recognized the need to prevent pooling of water on wall tops, and the devastating effect of water carving channels into adobe as if flows down the face of the wall. They suggested emulsion-amended adobe bricks as wall caps "virtually immune to erosion", and amended plaster as being resistant to channeling. But their enthusiasm was tempered in their realistic summary: "Though it is apparent at Hasanlu the system of preservation used there can retard erosion, no means has been devised to halt it indefinitely."[27]

In 1976, Butterbaugh and Pigott also tested the performance of E-330-amended earth in Chimaltenango, Guatemala. There, they constructed a test wall, a prototype of a wall designed to be more resistant to seismic damage, by stringing chicken wire between vertical wooden poles, and plastering both sides with amended mud. They made a similar unamended wall which was sprayed with 3% A-21 in toluene. After 36 months, they reported that both walls were holding up well, with hand prints still visible in the earthen surfaces.[28] This report also revealed that Butterbaugh finally returned to Casa Grande Ruins National Monument in Arizona. In cooperation with the Western Archaeological Center of the National Park Service in Tucson, a test wall at Casa Grande was sprayed with A-21 in toluene. After 28 months, Butterbaugh reported that the treated wall was holding up well, when compared to an untreated wall.[29]

In this same report, a reference was found describing adobe bricks made with "Florida clay", Rhoplex E-330 and water (1:3) that Butterbaugh placed on the roof of the University Museum in Philadelphia in July, 1975.[30] An inquiry revealed that the bricks were still on the roof, and had remained exposed to the weather since their installation. Butterbaugh was contacted and he gave his permission to sample one of the bricks, which proved to be in excellent condition. One brick was

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27 Ibid, 167.

28 Darrell J. Butterbaugh and Vincent C. Pigott, "MASCA Mudbrick/Adobe Conservation Interim Report", *3rd International Symposium on Mudbrick (Adobe) Preservation* (Ankara: ICOM/ICOMOS, 1980), 23.

29 Ibid, 24.

30 Ibid, 25-26.

cracked but otherwise the soil (which appeared to be primarily sand) was still firmly bonded, with only a thin surface layer of biological growth testifying to 20 years of exposure to the humid Delaware River Valley weather.

Figure 5. Placed on the University Museum roof in Philadelphia in 1975, these E-330 amended adobe bricks made by Darrell Butterbaugh were still in sound condition in 1995. Although a particle size analysis of the soil was unavailable, the soil appeared to have a high sand content. A quarter is shown for scale.

Concurrent with some of Butterbaugh's work, two researchers at the Engineering Experiment Station of the College of Engineering at the University of Arizona, Tucson, began a series of tests in 1973 of 20 consolidants and combination of consolidants on behalf of the National Park Service's Arizona Archeological Center, also in Tucson. Included in their list of tested chemicals were Rhoplex E-330 and E-826 (both mixed 1:3, Rhoplex to water) obtained from Chaco Canyon where Butterbaugh had introduced the materials in 1973.[31] Instead of field tests, the consolidants were tested on small manufactured adobe cubes. Held with forceps, the cubes were dipped in consolidant for approximately five seconds (achieving 1/2" of penetration) and allowed to dry. They were rated according to their performance in seven areas: appearance, freezing/thawing, wetting/drying, soaking in water, abrasion, heating/cooling, and accelerated weathering.

Neither of the Rhoplex treatments "passed" any of the tests, failing criteria set by the researchers.[32] In retrospect, the failure of the acrylic emulsions as externally applied consolidants is not surprising. The limited penetration of the milky, water-based, material would virtually ensure the development of an impregnated layer on the outside of the treated adobe, with physical properties

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31 James D. Kriegh and Hassan A. Sultan, *Final Report, Feasibility Study in Adobe Preservation: Casa Grande National Monument and Fort Bowie National Historic Site* (Tucson: University of Arizona, College of Engineering, 1974), 28.

32 Ibid., 66-7.

incompatible with the untreated core. But this failure of Rhoplex E-330 did not discourage further experimentation with this material.

Continuing the work Butterbaugh began at Chaco Canyon was Dennis Fenn, a research scientist then with the National Park Service's Western Archaeology Center in Tucson, Arizona. In a series of extensive tests at Chaco Canyon, Fenn and his collaborators tested dozens of commercially available chemicals with the hope of finding one or more that could help retard the erosion of the stone and earthen materials found at National Park Service sites in the Southwest.

He began in July, 1975, at a pueblo site on Chaco Wash, Bc-236, excavated in 1958 and threatened by stream bank erosion. Three products were chosen for a mortar test at this site: Bakelite VMCH Vinylite, a carboxylated vinyl chloride resin; Primal (Rhoplex) 863; and Rhoplex E-330. The two acrylic emulsions were mixed with water (10% solids) and earth, and the amended mud was used as mortar. The Vinylite was sprayed on unamended earthen mortar. After one year, the site was revisited. The untreated control mortar displayed moderate to severe erosion. The Vinylite treated mortar was badly discolored in sections, but uneroded. The E-863 section had begun to erode, in some sections as badly as the untreated sections. The E-330 section had cracked badly (this was attributed to bentonite clay in the soil, and not to the polymer) but no erosion was visible.[33]

In October, 1975, the study was expanded to include a new site known as Lizard House. Additionally, six new Rohm and Haas polymers were added to the experiment, all acrylic emulsions except for Acryloid A-21. (Vinylite was not tested on this site.) The treatments consisted of repointing the walls with earthen mortar prepared using the chemical solutions at 10% solids in place of water to make the mud. Adobe bricks 1' x 1' x 3-1/2" were formed from each earthen mortar mix and placed on the ground to weather. After nine months the test walls were inspected. Fenn

33 Dennis B. Fenn, "First Annual Report, Chemical Stabilization of Prehistoric Structures at Chaco Canyon National Monument" 8 August 1976, Intermountain Cultural Resources Center, National Park Service, Santa Fe, 1-4.

concluded that the E-330 was performing best, showing the least erosion, but rendering the mortar slightly darker.[34]

Also in October, Fenn established a test site at a pithouse near the base of Fajada Butte at Chaco Canyon, SJ-299, to examine the effectiveness of all nine previously tested chemicals as sprays (concentration of 10% solids). Each chemical was sprayed on a section of the pithouse, from rim to floor. The spray coated the earthen wall, and also the horizontal capping at the top of the wall, and a bench between the floor and the capping. Nine months later, the site was examined and some general observations were made. Because of the lack of significant penetration, all the horizontal surfaces had failed. The vertical surfaces were fairing better.[35]

Expanding the test in July, 1976, construction of test walls of Cliff House sandstone was begun near the visitor center at Chaco Canyon. Each test wall was approximately 4' long and 3-1/2' high, with an average of 11 courses of sandstone. Fenn selected 13 new chemicals to add to the trial from a list of 95 products tested by the National Bureau of Standards' Center for Building Technology. These, plus four Rohm and Haas products including Rhoplex E-330 and Acryloid A-21, brought to 17 the number of chemicals to be tested on the new sandstone walls.

Prior to pointing the walls with amended mud, each wall was sprayed with its assigned chemical and allowed to dry. Then a earthen mortar was mixed with the selected chemical and applied to the joints in the masonry. Fenn observed that most of the sprays discolored the stone. He also noted that the organic solvent materials failed as mortar additives, causing the mortar to dry to a loose grained powder. He attributed this effect to the flocculating properties of the organic solvent, interfering with the bonds between the clays and sand.[36]

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34 Ibid, 8-15.
35 Ibid, 16-21.
36 Ibid, 22-26.

The next year Fenn issued another report, listing observations about the trials begun in 1975 and 1976, and developments in the experimental program since the last report.[37] The final two rooms of the test wall structure were completed, a perimeter wall was added, and water was supplied to the base of the test walls through a drip irrigation hose so that capillary rise from the soil foundation would accelerate stone and mortar deterioration. Additional chemicals were added to the test, making 31 in total, 21 water-based and 10 organic solvent-based. An *in situ* polymerization of methyl methacrylate was attempted on one wall.

At Bc-236, only the E-330 proved to be effective at significantly slowing mortar deterioration. At Lizard House, all eight of the chemicals tested were effective at slowing mortar erosion, though some were better than others. The test site at the base of Fajada Butte, SJ-299, continued to erode, demonstrating the ineffectiveness of spray treatment with the selected chemicals.[38]

Fenn, with John Deck, issued his third, and last, annual report on the chemical stabilization trials at Chaco Canyon in 1978.[39] Two new chemicals were added to the test wall "ruin", as well as a 5:1 soil-cement, and amended adobe bricks similar to the ones at Lizard House were made and left flat on the ground to weather. In addition, treated soil samples were subjected to several laboratory tests, including compressive strength (wet and dry) and a seven-day soaking test. The soil used for the earthen mortars at this test site was identified as soil from the spoil bank from the sanitary landfill at the park. That soil, labeled Chaco Canyon South Gap, was characterized as part of this report.

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37 Dennis B. Fenn, "Second Annual Report, Chemical Stabilization of Prehistoric Structures at Chaco Canyon National Monument" 28 December 1977, Intermountain Cultural Resources Center, National Park Service, Santa Fe.

38 Ibid, 7-17.

39 Dennis B. Fenn and John R. Deck, "Third Annual Report, Chemical Stabilization of Prehistoric Structures at Chaco Canyon National Monument" 20 December 1978, Intermountain Cultural Resources Center, National Park Service, Santa Fe.

Based on the results of the mortar tests, the weathering of the adobe bricks, and the laboratory test results, Fenn made ten recommendations for the use of chemical amendments.[40]

Negative Recommendations:

1. Chemical products having hydrocarbon solvent bases should not be used for soil amendments.
2. Spray applications of the tested chemicals should not be used to stabilize pit house walls.
3. Products that failed the field tests should not be used to make amended earthen mortar.
4. Chemicals should not be used in concentrations of less than 10% chemical solids in the aqueous solution.

Positive Recommendations:

1. Rhoplex E-330 should be used to make amended earthen mortar and capping.
2. E-330 should be mixed so that it contains approximately 13% chemical solids by weight (1:2.5, E-330 to water).
3. When possible, the soil used should be approximately 70% sand, 20% clay and 10% (or less) silt.
4. The Chaco Canyon research project should be monitored for five more years.
5. An economic analysis should be conducted to confirm the economic sense of using an acrylic emulsion to lengthen the maintenance cycle.
6. Pithouse stabilization research should be given a high priority.

Fenn revisited Chaco Canyon in 1979, and reported on the results of the three field sites and the test wall "ruin". No surprises were found, but it should be noted that although Rhoplex E-330 was recommended for use, 10 other polymer emulsions were also performing satisfactorily in the test walls. E-330 had an additional 10 months of weathering time over all the others, however. The

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40 Ibid, 2.

condition of the methyl methacrylate polymerized in place, or the soil-cement, were not reported.[41] In the same report, Fenn described chemical research on mud plasters at Bent's Old Fort National Historic Site in Colorado. The results were similar to the findings at Chaco Canyon, with the exception of the spray-applied chemicals which performed satisfactorily at Bent's Fort. Fenn speculated that the products behaved differently on freshly applied plasters than they did on weathered earthen surfaces.[42]

The use of Rhoplex E-330, and related polymer emulsions, spread like ripples in a pond from Chaco Canyon to other National Park Service-administered ruins; to Aztec Ruins, to Mesa Verde, to Pecos, and beyond to related sites in the Four-Corners region. But Dennis Fenn's original recommendations didn't always travel with the material, and years of varied experience have brought changes to Fenn's original recommendations. Fenn recommended a sandy soil, perhaps because the soil he used at Chaco Canyon successfully was a sandy soil. But suitable sandy soils are not always readily available at some sites. Color and texture compatibility with remaining original material seem to be the driving concerns for soil selection today. Fenn recommended a 1:2.5 E-330 to water mix, and that is still the approximate concentration used at the three sites selected for study. When the polymer arrived at Aztec Ruins in 1983 it was used full strength, because the recommendations for dilution did not accompany the polymer.

E-330 has been used as a mortar amendment at Mesa Verde, Chaco Culture and Aztec Ruins since the late-1970s or early 1980s. Along with other amendments, it also has been used as a mortar or adobe amendment at several other National Park Service locations in the Southwest since the late-1970s.

41 Dennis B. Fenn, John R. Deck, Walter P. Herriman and John R. Vincent, "Chemical Stabilization Methods Research at Chaco Canyon National Monument and Bent's Old Fort National Historic Site" n.d., Intermountain Cultural Resources Center, National Park Service, Santa Fe, 11.

42 Ibid, 19.

3
FIELD OBSERVATIONS

In October, 1994, the author visited each of the three sites investigated for this report, and interviewed the maintenance chief or stabilization archaeologist. Samples of amended mortar and modern repair materials were collected and returned to the Architectural Conservation Laboratory at the University of Pennsylvania in Philadelphia.

3.1 Mesa Verde National Park

Kathy Fiero is the archaeologist in charge of stabilization at Mesa Verde National Park. She supervises a crew of seasonal technicians who work spring through fall and are charged with, among other things, maintaining the cliff dwellings and surface pueblos. The crew also helps maintain important Anasazi dwelling sites at Hovenweep National Monument and Chimney Rock National Historic Site, which have no stabilization crews of their own. The crew of five is made up of predominately Navajo craftsmen who have a minimum of eight years experience. Raymond Begay, the crew leader, has spent 30 years tending the ruins at Mesa Verde.

Almost all the mortar repair work at Mesa Verde is made with Rhoplex E-330-amended soil. Only in sheltered sites is unamended mortar used. Fiero explained that the stabilization crew was prohibited from mining soil from within the park for use in repairs, so a combination of loess from the mesa top and yellow crusher fines from the adjacent Ute Mountain Indian Reservation were combined to make repair material. All the material is screened through a 1/8" mesh wire cloth before it is used. Texture and color are major concerns for the stabilization crew. The prehistoric mortar has a very fine texture, and the repair mortars, made with loess and crusher fines, are more sandy. Color is the major determinant of the ratio of red loess to yellow crusher fines. The mesa top

ruins are redder, so there the red loess predominates in earthen mortars, while the cliff dwellings require a more yellow, therefore sandier, mix.

Fiero has been at Mesa Verde since 1983, and she said the work with Rhoplex amended mortar began a couple of years before her arrival. Initially, they were using a 1:10 mix (Rhoplex E-330 to water), but now it is 1:3 or 1:2.5. The Rhoplex is stored in a heated workshop, and never used in freezing weather. The Park uses approximately one 55-gallon drum of E-330 each year; the material is not stockpiled.

In protected locations, Fiero said, the mortar repairs last many years. But in areas subjected to water, where snow stands against the wall, for example, the life expectancy is as little as two years. The mesa top ruins are more exposed than the partially sheltered cliff dwellings. At least three months of snow exposure and four months of freezing and thawing conditions can be expected at Mesa Verde. At sites such as Far View Ruins on the top of Chapin Mesa, some kiva walls stay perpetually damp.

At some ruins rebuilt and stabilized with cement, the stabilization masons left the bedding mortar recessed an inch or two from the face of the stone. Rhoplex-amended soil pointing mortar is placed in the joint, in front of the cement.

The failures of acrylic-modified mortar experienced by the stabilization crew at Mesa Verde are cracking of the mortar, occasional chunks falling out, complete disaggregation and a peculiar failure seen at Mesa Verde and not at the other two sites, a fine flaking disintegration, resembling delamination, although the mortar is not a laminar material.

When the crew makes repairs, they mix the Rhoplex and water in a bucket, the proportions estimated by eye, and then add the E-330 and water mixture to the soil. The mortar stands in a bucket until it is used, and kept damp until it is applied to the wall. The mortar is usually trowelled into the joints. Various techniques have been tried to prevent cracking and ensure a longer lasting repair, including placing burlap over the repair work to prevent rapid drying, and reworking the

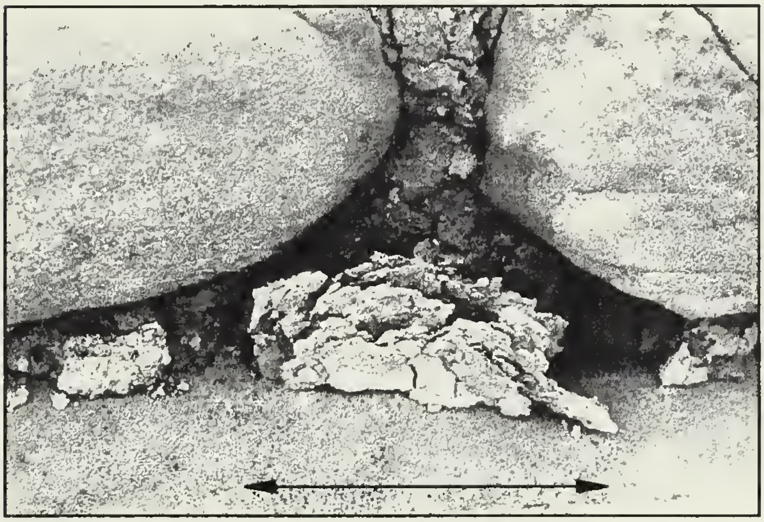

Figure 6. Flaking deterioration of the acrylic emulsion-modified earthen mortar was seen at some Mesa Verde National Park locations. A similar phenomenon was observed in the laboratory with Mesa Verde Blend earthen mortar. (Arrow is approximately two inches.)

earthen mortar as it dried, but they were advised by Rohm and Haas that reworking might break the polymer bonds within the mortar.

Rohm and Haas representatives have been consulted over the years, but they agree that they are not sure how the polymer reacts with soil. Its effect on concrete is more predictable, because the base materials are more uniform.

Samples of sound and disintegrating mortar from Far View Ruin and Coyote Ruin were collected and returned to the Architectural Conservation Laboratory for examination.

3.2 Aztec Ruins National Monument

James Brown is in charge of stabilization at Aztec Ruins National Monument, where Rhoplex E-330 has been used since approximately 1983. Brown, at Aztec Ruins for 16 years, uses a blend of three different soils for mortar repairs and capping. The formula, 2 parts silt, 3 parts clay and 6 parts sand, is the product of trial and error, a workable mix with minimal shrinkage that presents an appearance similar to existing historic mortars. Rhoplex E-330 is mixed with water in proportions of 1:2, the highest proportion of the three sites. At Aztec Ruins, amended mortar is used for wall capping as well as joint pointing, and capping is where Brown has found the amended mortar

to be least satisfactory. Cracks are the major problem. Adding more sand helps alleviate the cracking problem, but the larger proportion of coarse particles alters the visible appearance of the repair. Texture seems to be a bigger concern than color at Aztec Ruins, perhaps because all the soil components are similar in color to each other, and similar to the masonry and existing historic mortar in the ruin. The addition of a fine masonry sand is being considered to help alleviate cracking.

Brown also has seen some disaggregation failure of the mortar, although that is not a common problem at Aztec Ruins.

The amended mortar is mixed in a 5-gallon bucket and usually used in one day. Sometimes, if mortar remains, the bucket is sealed tightly and used the next day. Mortar repairs are not started when the temperatures fall below 40°F.

Figure 7. Cracking of acrylic emulsion-modified soil capping is a problem experienced at Aztec Ruins National Monument. But the cracks are a function of the mineral components of the soil mix, particularly the clay minerals, and not the acrylic amendment. The cracks are a cause for concern because they allow more water to enter the interior spaces of the walls.

The major advantage of E-330, according to Brown, is its colorlessness. Parts of Aztec Ruin, like other ruins, are a patchwork of white cement, original mortar, and mortar modified with bitumen (asphalt) emulsion. The bitumen-modified mortar, a durable material remaining from early stabilization work, exhibits a gray cast. (See *Appendix A* for an SEM image of Aztec Ruins bitumen mortar.)

Repairs of sheltered areas at Aztec Ruins are made with unamended mortar, and stones exposed to weather are laid with unamended mortar recessed 1" to 2" from the stone face. The joint is then pointed with amended mortar. Walls are pre-wet before repairs are made. (Brown said that

some walls shed water, indicating prior chemical treatment, but no research of chemical treatments at Aztec Ruins was undertaken for this research.)

The amount of work performed at Aztec Ruins varies from year to year, depending on the amount of damage that appears in the spring. Brown said that he and his crew of two use approximately one 55-gallon barrel of E-330 each year.

3.3 Chaco Culture National Historical Park

Archaeologist Dabney Ford and Masonry Foreman Cecil Werito at Chaco Canyon are responsible for repair and maintenance of the ruins near Chaco Wash and on the adjacent plateaus. A significant finding was that the maintenance crew at Chaco Canyon was no longer using Rhoplex E-330 as a soil amendment, but instead had switched to Daraweld C, a vinyl acetate emulsion.[43] (Daraweld C was another product tested by Fenn at Chaco Canyon, where it performed well.) Werito believes that Rohm and Haas changed the formulation of E-330 making the amended mortar more difficult to work with. (The company maintains the formula has not changed.) The crew at Chaco Canyon does not make mortar repairs every year, and had not made mortar repairs for two seasons.

Soil for repairs to the ruins in Chaco Canyon come from a Bureau of Land Management (BLM) site approximately 1-1/2 miles north of the park boundary, although Werito believes that soils from within the park near the sites make the best repairs. E-330-amended Tsin Kletsin soil is still in service at Tsin Kletsin pueblo approximately 20 years after installation. Tsin Kletsin is a relatively isolated ruin, and the repair crew was allowed to use soil from the site. Previous soil for mortar

43 Daraweld C is a concrete bonding agent manufactured by Grace Construction Products Co., Cambridge, MA.

repairs came from South Gap (the soil Fenn used). The switch from E-330 to Daraweld C roughly corresponds to the switch from South Gap soil to soil from the BLM quarry.

Amended material is used for pointing, and for capping at some sites. Mortar repairs are normally made from mid-April to mid-October, depending on acceptable weather. Ford said that repairs were usually not made in temperatures below 55°F, although it has been used for deep repointing when the temperature was expected to fall below freezing. Leftover mortar used to be stored overnight, but now is discarded at the end of each day. The proportions of E-330 to water used were 1:3.5 or 1:4. A 1:2 mix is unworkable, according to Werito.

The problems experienced with amended mortar at Chaco Canyon are cracking and disaggregation, sometimes within a year. The problems are always associated with water; if the mortar is kept dry, it is durable. Previously, according to Werito, if the mortar got wet it softened, then hardened again. Now, if it gets wet, it softens and then crumbles. Deteriorating mortar in a kiva at Pueblo Bonito was inspected. On a shady face of the kiva, the wall was damp, and the amended mortar soft and crumbly. Adjacent was a dry section of the wall with amended mortar showing no evidence of deterioration.

The test walls built for Dennis Fenn in 1976 remain in place. The E-330 mortar put in the test wall during the original trial was sampled during a visit in October 1994. It is still in sound condition and appears to be relatively uneroded. (See *Appendix A* for an SEM image of this mortar.)

3.4 Other Sites

The stabilization crew at Mesa Verde also performs work at Hovenweep National Monument, using E-330-amended mortar and a mix of pink and red soils from the mesa top near Square Tower Unit, in a blend of 1:1 or 2:1 red to pink.

The crew also has performed ruin repairs at Chimney Rock Archaeological Area using E-330 and calcium aluminate. (Calcium aluminate is an inorganic cementitious material made from bauxite and limestone, primarily for refractory use.) Two soils have been used for these repairs, Chimney Rock Lower, from a road cut on the lower part of the mesa, and Chimney Rock Middle, from a road cut halfway up the mesa. Repairs made in the fall with E-330 and Chimney Rock Lower soil failed over one winter, turning into loose soil by spring.

Some of the calcium aluminate repairs have lasted seven years, at a very exposed mesa-top site. The material must be allowed to dry out before it freezes and has a gray color, which complicates the task of making an earthen mortar visually compatible with existing mortars.

3.5 Climate

The climate at the three Colorado Plateau sites is characterized by cold winters, although the average temperature in the coldest months never drops below 20°F, and warm summers, with the temperature rarely exceeding 100°F. Annual precipitation at Aztec Ruins and Chaco Canyon is in the range of 9-10 inches per year, and approximately twice that at Mesa Verde. The region is prone to thunderstorms, and precipitation falls year-round. In the winter snow can set on wall tops or at the base of walls, melting and soaking into the adjacent masonry when the sunlight strikes the surface or the air temperature rises.

The effect of the year-round precipitation guarantees that earthen mortars in exposed locations can be wet at any time. The climate, with temperatures hovering near freezing in the winter, and alternating sun and showers nearly year-round, ensures that the decay mechanisms of wetting and drying and freezing and thawing have ample opportunity to practice their destruction.

Chaco Canyon has an average of only 117 frost-free days each year, yet the sun shines during 70% of the daylight hours, warming the sandstone and earth. The prevailing westerly winds carry fine abrasive particles which scour the ruins.[44]

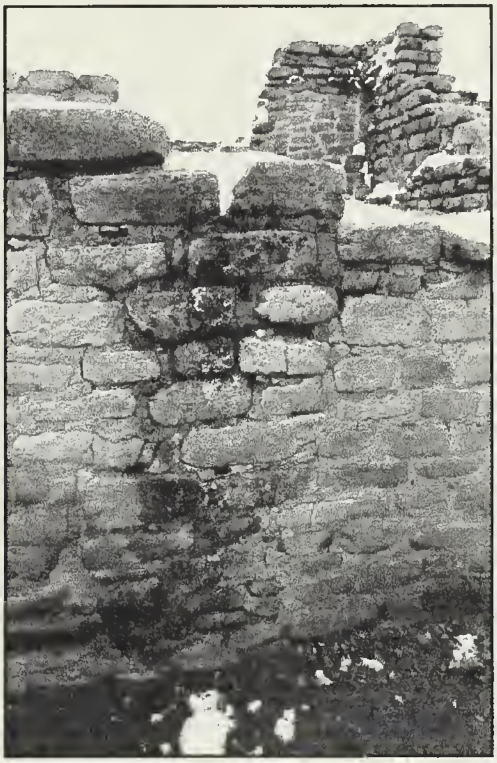

Figure 8. Water in the form of melting snow is one of the deterioration mechanisms at work on soil mortars in the Southwest. This photograph of Far View Ruin at Mesa Verde National Park reveals the wet stain of water flowing over the wall face after a fall snow. The wall is not wetted equally, and some areas are wet more often, and remain wet longer, leading to soil mortar erosion. (See *Appendix A* for SEM views of sound and deteriorated mortar from this ruins site.)

The information in the following tables was selected from weather data provided by resource specialists at each National Park Service site, and illustrates the typical temperature and precipitation conditions found in this climatic region, with an emphasis on the winter months when freezing conditions are most likely to occur.

44 Katherine Dowdy and Michael R. Taylor, "Investigations into the Benefits of Site Burial in the Preservation of Prehistoric Plasters in Archaeological Ruins", *7th International Conference on the Study and Conservation of Earthen Architecture* (Lisbon: DGEMN, 1993), 481.

MESA VERDE WEATHER DATA

Weather Feature	Period/No. of Years	Data	Period/No. of Years	Data
Mean annual precipitation	1922-1987/60	18.9 inches	1988-1993/6	18.9 inches
Mean annual temperature	1922-1987/58	50°F	1988-1993/6	47°F
Mean number of days/year with precipitation ≥ 0.1 inches	1922-1987/38	54		
Mean number of days/year with snow depth ≥ 1.0 inches	1922-1987/19	94		
Highest recorded temperature	1922-1987/60	102°F		
Lowest recorded temperature	1922-1987/60	-20°F		
Mean January temperature	1922-1987/65	29°F	1988-1993/6	25.5°F
Mean February temperature	1922-1987/65	33°F	1988-1993/6	32°F
Mean March temperature	1922-1987/65	38°F	1988-1993/6	38.5°F
Mean November temperature	1922-1987/65	39°F	1988-1993/6	35.5°F
Mean December temperature	1922-1987/65	31°F	1988-1993/6	26.5°F

Table 2

AZTEC RUINS WEATHER DATA

Weather Feature	Period/No. of Years	Data	Period/No. of Years	Data
Mean annual precipitation	1895-1991/86	9.7 inches	1984-1993/10	11.5 inches (approx.)
Mean annual temperature	1895-1991/75	51°F		
Mean number of frost-free days/year (32°F)	1895-1991/44	139		
Highest recorded temperature			1984-1993/10	104°F
Lowest recorded temperature			1984-1993/10	-18°F
Mean January temperature			1984-1992/9	29°F
Mean February temperature			1984-1992/9	37°F
Mean March temperature			1984-1992/9	44°F
Mean November temperature			1984-1992/9	40°F
Mean December temperature			1984-1992/9	30°F

Table 3

CHACO CANYON WEATHER DATA

Weather Feature	Period/No. of Years	Data	Period/No. of Years	Data
Mean annual precipitation	1933-1992/60	9.1 inches	1992-1994(9 mo.)/2.75	7.7 inches (approx.)
Mean annual temperature	1933-1992/44	50°F		
Mean number of frost-free days/year (32°F)	1933-1992/42	117		

Table 4

4
TESTING AND CHARACTERIZATION

4.1 Soil Characterization

All 17 of the Southwestern soils (including individual components of the blended soils) were characterized according to the following nine criteria:

- color (dry and moist)
- pH
- particle size distribution
- soil particle description
- soil density
- qualitative soluble salt analysis
- acid-soluble (carbonate) content
- Atterberg limits (liquid and plastic limits)
- shrinkage (linear and volumetric)

The three soils currently used for mortar repairs – Mesa Verde Blend, Aztec Blend and Chaco BLM Quarry – plus Chaco Canyon South Gap, the soil used by Fenn at the test walls at Chaco Canyon, also were analyzed by x-ray diffraction to determine clay mineralogy, and were examined to determine bulk mineralogy.

4.1.1 Soil Characterization Description

Color – Soil colors were determined by comparing soil samples with a set of 199 standard soil colors published by Munsell Color. The color chips are arranged on cards according to the Munsell notation in a loose leaf notebook. The cards have holes through the pages beneath the color

chips, and the soils were observed through the holes. The color best matching the soil was recorded, or if the color fell between two chips, an intermediate notation was interpolated.

The Munsell system divides color into three variables called Hue, Value and Chroma. According to the Munsell system, "The Hue notation of a color indicates its relation to Red, Yellow, Green, Blue, and Purple; the Value notation indicates its lightness; and the Chroma notation indicates its strength (or departure from a neutral of the same lightness)."[45]

A typical soil color notation is 5YR 3/4. The Hue is denoted by the 5YR portion of the symbol, indicating where the color falls in the range of colors from purple to red. In this example YR means yellow-red. The second number, 3/, is the Value, or how dark or light the color is. A Value of 1 is very dark, almost black, while a Value of 9 is very light, almost white. Finally, the third number, /4, is a measure of the Chroma, or saturation of the color, ranging from 0, a neutral gray of the same Value, to 8, a vivid yellow-red of the same Value.

The colors of the soils and the Munsell chart were compared according to ASTM D1535, *Standard Test Method for Specifying Color by the Munsell System*[46], using north light, mid-afternoon. The soils were loose, and one comparison was made with air-dry soil, and another after the soil was moistened (but not saturated) with water. These two notations represent two commonly encountered field conditions.

Particle Size Distribution – Soil particle size and size distribution were determined by sieving and by the sedimentation method, as described in ASTM Standard D422. The soil was soaked in a sodium metaphosphate solution to disperse the clay particles, which tend to flocculate, and sieved wet through a 0.075 mm sieve. The portion retained on the sieve was oven dried, and the fraction passing was placed in a 1000 ml glass sedimentation cylinder. The oven-dried portion was sieved through a full set of soil sieves, and the fine portion passing the 0.075 mm sieve was added to

45 *Munsell Soil Color Charts* (Baltimore, MD: Macbeth Division of Kollmorgen Instruments Corp., 1988).
46 "D1535, Standard Test Method for Specifying Color by the Munsell System", (Philadelphia: ASTM, 1993).

the sedimentation cylinder. The cylinder was filled with deionized water and agitated, and hydrometer readings were taken at regular intervals. This test relies on Stoke's Law, which describes how small spherical particles fall through a liquid, to predict the distribution of soil particles in the range of 0.075 mm to less than 0.001 mm.[47] It is only an approximation because soil particles, particularly clay particles, are not spherical, but it has been demonstrated to give reasonable results with basic equipment.

Many classification systems are used for describing the range of particle sizes in soil. For this report, the ASTM particle size convention was adopted:[48]

Gravel	76.2 mm – 4.75 mm
Coarse Sand	4.75 mm – 0.075 mm
Fine Sand	0.075 mm – 0.02 mm
Silt	0.02 mm – 0.002 mm
Clay	< 0.002 mm

Soil Particle Description – The > 0.075 mm fraction of soil reserved from the particle size distribution test was examined under a Nikon SMZ-U stereo microscope with a Foster 8345 quartz halogen fiber optic light source, and general observations were recorded, including particle shape (roundness and sphericity), color and the presence of organic material.[49]

Soil Density – The accurate determination of particle size distribution described in ASTM Standard D422 requires knowledge of the soil's density. The density of soil was determined by boiling a known mass of soil in a vessel of a known volume, to remove air from the soil. After allowing the soil and water to cool, the vessel was topped off with water, and the soil density was

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47 Jeanne Marie Teutonico, *A Laboratory Manual for Architectural Conservators* (Rome: ICCROM, 1988), 83.

48 "D422, Standard Test Method for Particle-Size Analysis of Soils", (Philadelphia: ASTM, 1993); and "D653, Standard Terminology Relating to Soil, Rock, and Contained Fluids", (Philadelphia: ASTM, 1993).

49 P. Bullock and others, *Handbook for Soil Thin Section Description* (Wolverhampton, UK: Waine Research Publications, 1985), 30-32.

calculated from the weight of the combined soil and water, the temperature of the water, and the weight of the same vessel filled with water at the same temperature. The procedure is described in ASTM Standard D854.[50]

Qualitative Soluble Salt Analysis – The presence of significant soluble salts in each soil was checked by soaking a dry soil sample of a known mass in deionized water for three hours, filtering the mixture, and qualitatively testing the filtrate for salts (chlorides, sulfates, phosphates and nitrates) by using microchemical tests. The procedure for the microchemical tests requires that each positive result be confirmed using another reagent, and each negative test be confirmed by adding a drop of a dilute solution containing the suspected salt to check the reagent. Knowledge of salt content of the soils is important. A high level of soluble salt could interfere with the mechanism of a consolidant, or affect the weathering of earthen materials. The microchemical tests used are included in Appendix C.

Acid-Soluble (Carbonate) Content – Southwestern soils often contain significant amounts of carbonates, calcite or calcium carbonate ($CaCO_3$), and dolomite ($CaMg(CO_3)_2$). In a survey of adobe soils in New Mexico, calcite was found in 99% of the samples tested, primarily in the clay-sized (< 0.002 mm) fraction, but also in the silt- and sand-sized fractions. The predominance of clay-sized particles indicates the calcite is pedogenic, or formed-in-the-soil, rather than fragments of a weathered calcite rock, such as limestone. Calcite in Southwestern soils is called caliche, and can be present at very small size where it seems to play an important part in binding adobe soils. When wetted, the calcite in these soils is mobilized, and deposited in the pores of the drying adobe, binding the particles together. If the caliche deposit (often on the surface of the soil) is harder and more massive, the particles of caliche act as aggregate, and not as a binder.[51]

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50 "D854, Standard Test Method for Specific Gravity of Soils", (Philadelphia: ASTM, 1993).

51 Edward W. Smith and George S. Austin, *Adobe, Pressed-Earth, and Rammed-Earth Industries in New Mexico* (Socorro, NM: New Mexico Bureau of Mines and Mineral Resources, 1989), 19.

A simple variation of a standard mortar analysis was performed on the soils to determine the acid-soluble fraction. It is assumed that the predominate acid-soluble component of these soils is calcium carbonate. First, two or three drops of 15% HCl were placed on a soil sample on a spot plate. If effervescence was observed, the complete acid-digestion test was performed. Briefly, the mass of the soil before and after being washed in 15% HCl was compared, and the difference calculated to be the acid-soluble fraction.[52]

pH – The pH readings were made with a Cole-Parmer "pHep" pocket-sized instrument (range 0.0 to 14.0, resolution to 0.1, accuracy ±0.2), calibrated with ATI-Orion "perpHect Buffer", according to ASTM D4972. Two samples of each soil, 10 grams each, were tested. One was soaked for one hour in deionized water and the other in a 0.01M $CaCl_2$ solution. The $CaCl_2$ test helps minimize the dilution effect of water-only pH tests, and results in slightly lower pH values, due to the release of aluminum ions which hydrolyze.[53]

Soils with lower pH levels will tend to flocculate; the clay particles will clump together. Soils with higher pH levels have clay particles which tend to disperse.[54] (It is for this reason that soils are treated with a basic sodium compound solution before the sedimentation test for particle size. The compound helps disperse the clays in the test soil.)

Atterberg Limits – Of the original seven "limits of consistency" defined by Swedish scientist Albert Atterberg, only three are in common engineering usage: the liquid limit (LL), the plastic limit (PL) and the shrinkage limit. Two of Atterberg's limits were used to characterize the Southwestern soils. Knowledge of the liquid limit and plastic limit can provide clues about the performance of soil in architectural applications. Two additional characterization values, the

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52 Teutonico, 113-115.

53 "D4972, Standard Test Method for pH of Soils", (Philadelphia: ASTM, 1993).

54 Werner S. Zimmt, *Soil Selection for the Preservation of Historic and Prehistoric Adobe Structures* (Tucson, AZ: Western Archaeology Center, National Park Service, 1993), 5.

plasticity index (PI) and the coefficient of activity (CA), can be calculated from the plastic limit and liquid limit, and the amount of clay in the soil.

The liquid limit of a soil is defined as "the water content, expressed as a percentage of the mass of the oven-dried soil, at the boundary between the liquid and plastic states".[55] This limit is determined by using a Casagrande device (named after another soil scientist, Arthur Casagrande), which repeatedly drops a sample of wet soil scored with a groove until the soil flows and closes the groove. The moisture content of the soil is then calculated. The device is calibrated and the test methodical so that the arbitrarily defined liquid limit can be calculated from repeated performances. The standard is ASTM D4318.[56]

ASTM D4318 also details the procedure for determining the plastic limit of soils. The plastic limit of a soil is defined as "the water content, expressed as a percentage of the mass of the oven-dried soil, at the boundary between the plastic and semi-solid states."[57] It is determined by repeatedly rolling a soil sample into 3.2 mm threads, until the soil crumbles, and then calculating the water content of the soil. For a range of soils, the plastic limit varies less than the liquid limit, and is somewhat related to the surface area of the clay particles, though not in direct proportion.[58]

The plasticity index is obtained by subtracting the liquid limit value from the plastic limit value. Higher values for the PI usually predict greater expansion when soil is saturated with water.[59] Also, strength of a soil is said to increase when the PI increases.[60]

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55 Teutonico, 102.

56 "D4318, Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", (Philadelphia: ASTM, 1993).

57 Teutonico, 96.

58 Raymond N. Yong and Benno P. Warkentin, *Soil Properties and Behaviour* (New York: Elsevier Scientific Publishing Company, 1975), 66.

59 James R. Clifton, Carl R. Robbins, and Paul Wencil Brown, *Methods for Characterizing Adobe Building Materials, NBS Technical Note 977* (Washington, DC: National Bureau of Standards, 1978), 26.

60 Yong and Warkentin, *Soil Properties*, 62.

The coefficient of activity indicates the activity of the clays in the soil, and puts a value on the expansiveness of the mortar. The coefficient takes into account the amount of clay compared to the other, larger, particles in the soil.[61]

$$CA = \frac{PI}{\%\ \text{clays with diameter} \leq 2\mu}$$

Soils are rated "inactive" to "very active" depending on the CA:

- $CA < 0.75$ = inactive
- $0.75 < CA < 1.25$ = average activity
- $1.25 < CA < 2$ = active
- $CA < 2$ = very active

Shrinkage (Linear and Volumetric) – An important characteristic of earthen mortars is the ability to dry without unacceptable shrinkage. Clay minerals in the smectite (montmorillonite) family, such as bentonite, are particularly water sensitive, swelling when wet, shrinking (and therefore cracking) when drying. Measurement of linear shrinkage is a simple way to gauge the shrinkage potential of a soil using simple equipment.[62]

Small troughs were made from split one-inch inside diameter PVC pipe, approximately 5-5/8" long, with plastic ends glued to the troughs. Soil thoroughly mixed with water to a workable consistency was packed into the troughs and allowed to partially dry, until it could be tipped out and completely dried in an oven. The dry length of the soil compared to the length of the mold gives the amount of linear shrinkage, which can be calculated as a percent.

Measurement of linear contraction is not a way to determine the type or amount of clay in a soil sample; other analyses are needed to do that. But the amount of shrinkage is a practical measurement of soil performance, and that performance is determined by the constituents of the soil,

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61 Hugo Houben and Hubert Guillaud, *Earth Construction* (London: Intermediate Technology Publications, 1994), 59

62 K. H. Head, *Manual of Soil Laboratory Testing*, vol. 1, *Soil Classification and Compaction Tests* (London: Halstead Press, 1992), 107-109.

including sand, silt and clays. Sands experience very little linear shrinkage, and silts are only slightly more active than sands. The clay fraction is by far the most active. Kaolinite-type clays have a linear shrinkage rate of 3% to 10%; illites 4% to 11%; and smectites/montmorillonites 12% to 23%.[63]

Another measure of soil shrinkage is volumetric shrinkage, for soils shrink in all dimensions, not just length. However, the process for determining soil shrinkage by volume is more complex than simple linear shrinkage. The method used for many years involves casting a soil cake in a mold of known dimensions, and then immersing the dry soil in a dish of mercury, which would not be absorbed by the soil, and measuring the volume of the displaced metal. It is a straight-forward technique, but complicated by the fact that mercury is now a recognized toxin, and its use is discouraged.

A newer technique used in this study involves casting soil in a mold of known dimension, and then coating the dried soil with paraffin, and weighing the coated soil in water. By using all the knowns – soil weight, wax weight, density of wax, etc. – the unknown volume of dry soil can be calculated, and from that the percent shrinkage. This wax technique is detailed in ASTM Standard D4943.[64] Both shrinkage measurement techniques were used in this study.

Shrinkage also is related to the amount of water in the wet soil mix, more water often means more shrinkage. The amount of shrinkage apparently is not a linear function of the amount of water in the soil-water mix. High water content results in considerably increased shrinkage.[65]

X-Ray Diffraction – Clay mineral particles are too small to be seen with a common optical microscope. The only way to definitively identify clay minerals in a soil sample is to perform an

63 Houben and Guillaud, *Earth Construction,* 31.

64 "D4943, Standard Test Method for Shrinkage Factors of Soils by the Wax Method", (Philadelphia: ASTM, 1993).

65 Alejandro Alva Balderrama and Jeanne Marie Teutonico, "Notes on the Manufacture of Adobe Blocks for the Restoration of Earthen Architecture" in *Adobe: International Symposium and Training Workshop on the Conservation of Adobe,* Lima-Cusco, Peru, Sept. 10-22, 1983, 49 (Rome: UNDP/UNESCO/ICCROM, 1983).

instrumental analysis of some kind, usually x-ray diffraction (XRD), thermal analysis, or scanning electron microscopy. Of these, XRD is the most common, and if done by a skilled operator, a definitive method. XRD is effective for soil clay analysis because clay is a crystalline material, despite its decidedly uncrystal-like appearance. In the 1930s, x-ray diffraction proved to scientists that clays were a limited number of distinctly crystalline minerals, and not amorphous materials of irregular composition.[66]

The technique takes advantage of the fact that the wavelengths of x-rays are approximately the same as the internal spacing of the atomic particles within crystals, which results in diffraction of the x-rays when they pass through the crystalline material.[67] By passing x-rays through a prepared soil sample, and recording the diffraction patterns, a signature of the clay content can be obtained.

XRD was performed on the three soils or soil combinations used for mortar repairs at the National Park Service sites: Mesa Verde Blend, Aztec Ruins Blend and Chaco Canyon BLM Quarry. In addition, Chaco Canyon South Gap soil (Dennis Fenn's test soil) also was examined because it has performed exceptionally well when amended with E-330. New Mexico Alcalde Adobe was not tested because the soil is nearly all sand, it exhibited almost no shrinkage, and it is not, nor is it likely to be, a component of repair mortar at Anasazi ruins.

Another important characteristic in predicting soil performance in architectural contexts is the amount and type of organic material present. Decaying organic material renders soil unstable by increasing soil porosity, increasing acidity, causing clays to flocculate, and weakening compressive strength.[68] Visual observation of the Southwestern soils characterized for this report revealed relatively little organic content, mostly broken plant stems and fibers, and no significant amount of decayed organic material. The amount of organic material present is noted in Appendix B.

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66 Duane M. Moore and Robert C. Reynolds, Jr., *X-Ray Diffraction and the Identification and Analysis of Clay Minerals* (Oxford: Oxford University Press, 1989), 13.

67 Ibid., 11.

68 Balderrama and Teutonico, "Notes on the Manufacture of Adobe Blocks," 48.

4.1.2 Clay Minerals

Clay is from the Anglo-Saxon "Claeg", meaning "to stick".[69] And "stick" is precisely the property that makes at least a small amount of clay essential in a good adobe or mortar soil. Clay mineralogy is important because of the effects, primarily cohesion and dimensional instability, imparted to soils by clays. Clays tend to attract and hold water on their surfaces. Swelling clays such montmorillonite, also hold water between their layers, resulting in an increase in volume.[70]

Depending on the context, "clay" can mean either a soil particle of a certain size, usually smaller than 0.002 mm, or it can describe a mineral, specifically an alumino-silicate, an oxide of aluminum or silicon with metal ions sometimes substituted within the crystal. Kaolinite, illite, chlorite and smectite (also called montmorillonite) are examples of clay minerals found in Southwestern soils. Physical disintegration of rocks can produce clay-sized particles of quartz, mica, feldspar, etc., that are not clays and behave like their parent rock instead of like clay minerals. Particles smaller than 0.001 mm but larger than the molecular size are called colloids, and many clay particles are in this category. The very small mass, and corresponding relatively high surface area of these colloidal particles give them their unique properties of adsorption and plasticity.[71]

Clays are composed of tetrahedral and octahedral crystalline sheets of alumina (AlO_6) and silica (SiO_4) and it is the number and arrangement of these sheets, along with accessory elements, that determine the characteristics of different clay types. The two major arrangements are 1:1 layer, one tetrahedral and one octahedral layer, and 2:1 layer, a tetrahedral-octahedral-tetrahedral sandwich.[72] The 1:1 types are represented by serpentine minerals and kaolin mineral groups. One of the

69 Charles Thomas Davis, *A Practical Treatise on the Manufacture of Brick, Tiles and Terra-Cotta* (Philadelphia: Henry Carey Baird & Co., 1895), 26.

70 Brown, "Adobe II", 31.

71 Yong and Warkentin, *Soil Properties*, 21.

72 Moore and Reynolds, *X-Ray Diffraction*, 102-106.

kaolin minerals is kaolinite, one of the most ubiquitous aluminosilicates found in soils, a product of weathering, particularly of feldspars. An important feature of kaolinites is their stability in water; they swell less than other, more active, clays.[73]

The 2:1 types are more varied, and because of the extra electrically charged sites on the layer surfaces available for occupation by water and accessory elements, they have more varied properties. Some of the common 2:1 groups are illites, smectites, micas and chlorites. Illite, especially illite combined with smectite, is the most abundant clay mineral found in sedimentary rock. Illite is essentially non-expanding, but the related mineral, smectite, is quite active in water, especially the subgroup of smectite, montmorillonite.[74]

The amount of swelling in any clay type is also dependent on the particular ion present between the sheets of alumina and silica. Some common ions, in order of increasing swelling potential (and also diminishing plasticity) are aluminum, calcium, magnesium, potassium and sodium.[75] All clays swell some upon wetting, but high-swelling clays continue until they reach very high water contents. These clays are distinguished by large surface areas, smectites for example, and monovalent exchangeable ions, such as sodium. The small amount of swelling in clays is due to adsorbed water, but the greater swelling in smectites is due to electrical repulsion due to diffuse ion-layer penetration.[76] Surface area is also important. High-swelling clays are distinguished by very small particle size (volume), and resulting large specific surface: kaolin has a specific surface of 15 m^2/g; illite, 80 m^2/g; and montmorillonite (smectite), 800 m^2/g.[77]

73 Ibid., 123-125.
74 Ibid., 128-143.
75 Herman Salmang, *Ceramics: Physical and Chemical Fundamentals* (London: Butterworths, 1961), 49.
76 Yong and Warkentin, *Soil Properties*, 59.
77 Braja M. Das, *Introduction to Soil Mechanics* (Ames, IA: Iowa State University Press, 1979), 7-8.

4.2 Tests of Earthen Mortar Samples

> "Unlike the determination of...strength, the durability of a porous material is a characteristic which is subject to a set of complex laws and influences which cannot yet be determined by a single test. For design purposes all test data has to be not only reliable, speedy and reproducible but has to have some proven meaning related to the state of the world in which the material is to be used. This ability to predict behaviour in the building under the expected exposure conditions may be derived from either a theoretical model or from experimental results. Both of these have been investigated in recent years but as yet no reliable correlation has been fully established."[78]

A. J. Bryan was discussing soil-cement testing, but the statement is no less accurate when discussing the difficulty of predicting the performance of earthen mortars. The three soils used as mortar at the National Park Service sites – Mesa Verde Blend, Aztec Ruins Blend, Chaco BLM Quarry – and the New Mexico Alcalde adobe, were mixed with water and Rhoplex and subjected to the following physical tests or characterizations, deemed relevant to the environmental factors observed on site and the significant properties of the mortar:

- wetting/drying
- freezing/thawing
- modulus of rupture (four-point bending)
- water vapor transmission
- color (dry and moist, for each soil and Rhoplex combination)
- scanning electron microscopy (SEM)

Whenever possible, tests were conducted according to established standards or protocols. Unfortunately, there are few standards written specifically for earthen materials. Numerous soil mechanics texts and manuals were consulted for appropriate soil testing procedures. The three

[78] A. J. Bryan, "Soil/Cement as a Walling Material – II. Some Measures of Durability" *Building and Environment* 23, no. 4 (1988): 331.

physical tests, wetting/drying, freezing/thawing and modulus of rupture, employed modified ASTM standards for soil cements. The water vapor transmission test also is a slightly modified ASTM test.

Two tests, wetting/drying and freezing/thawing, were chosen to simulate the predominate weathering features of the sites, water and temperature. These tests stress the soil mortar specimens in the same way mortars in the field are stressed, although in a exaggerated manner. They were meant to test the ability of the polymer film to contain the stresses that occur within the mortar when the soil becomes wet and expands, or the stresses that occur when saturated soil freezes and expands.

The water vapor transmission test was designed to determine the effect of varying quantities of Rhoplex on the ability of the earthen mortars to transmit water vapor. Rhoplex E-330 is promoted for its ability to decrease the permeability of cement mortars, and it was presumed that it would have a similar effect on soil mortars, but the extent of that effect was unknown. Knowledge of the reduction of a mortar's ability to transmit water vapor in the laboratory because of increased polymer content could help explain mortar performance in the field.

A final test was included to help measure the effect of Rhoplex E-330 on particle adhesion, the modulus of rupture (bending) test. This test is unlike the other tests because it does not measure a condition or property thought to be a problem in the field. Rather it measures the principle property believed to be imparted to the soil by the polymer, increased strength, particularly the strength of the bonds between the soil particles.

Some of the samples for the wetting/drying test and the modulus of rupture test were cured at 40°F, below the glass transition temperature of E-330 (50°F) to see if any effect of low-temperature drying could be observed. A very few samples were cast, frozen, and then dried at ambient temperatures, to see what effect, if any, could be observed on the response to wetting/drying and modulus of rupture tests.

4.2.1 Earthen Mortar Test Descriptions

Water Vapor Transmission – Disks of amended soil were sealed in the open tops of plastic laboratory beakers containing 60 ml of water, and placed in closed glass chambers along with calcium sulfate desiccant. The beakers were weighed daily and the desiccant changed every three days. As water evaporated through the permeable material, the beaker assemblies lost weight. The greater the rate of loss, the more permeable the sample is to water vapor. In general, it is desirable for masonry materials to be permeable to water vapor, so that water is not trapped in pores of the material, and so that material that becomes wet can dry out. The test is governed by ASTM Standard E96.[79] Three disks of each soil/E-330 combination were tested. Also, one disk made with Mesa Verde soil and 100% E-330 was tested. As a control, two soil mortar disks were sealed in beakers with no water, and placed in two of the closed chambers. When these disks reached an equilibrium weight, indicating that the residual moisture present in the mortar specimens had evaporated, the test readings began.

Three calculated results of the water vapor transmission test are presented: water vapor transmission rate, water vapor permeability (a material property), and water vapor permeance (a performance evaluation, not a material property). The terms are defined and the values presented in Appendix C.

Modulus of Rupture – This is also called four-point bending. A prism of soil was supported on two blunt knife edges while a force was applied from above, through two more narrowly-spaced blunt knife edges, until the prism broke. Both the total load required to break the prism and its total

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79 "E96, Standard Test Methods for Water Vapor Transmission of Materials", (Philadelphia: ASTM, 1993).

deflection before failure were measured. This test is an indication of the flexibility of a sample and its resistance to bending. This test is governed by ASTM Standard D1635.[80]

When force is applied to the top of the prism, it fails at the bottom in tension, as the earthen mortar is stretched as it bends. Adobe soils are collections of various sized particles adhered primarily with clays. Like a wall made of bricks, the individual particles are strong in compression, but like the mortar joints in a brick wall are weak when pulled apart, adobe soils are weak in tension. Like the brick wall, the particles of soil are much stronger than the bonds between them. Also, soils with high clay content are reported to be weak in tension, partly due to shrinkage cracks.[81]

Four prisms of each soil/E-330 combination were tested, plus four prisms each from Chaco Canyon BLM Quarry and Mesa Verde Blend of each combination dried at approximately 40°F, and four prisms each of Mesa Verde Blend 25% and Chaco Canyon BLM Quarry 25% frozen, then dried at ambient laboratory conditions.

Freezing/Thawing – Cylinders of soil were placed on an absorbent pad, and allowed to wick up water. They were then cycled through freezing (at approximately -5° to -10°F) and thawing (at ambient laboratory temperatures), always remaining moist. Changes in condition of the soil cylinders were noted at the end of each thawing cycle. ASTM Standard D560 is the basis for this test, although the ASTM test calls for physical abrasion that these mortar samples could not have withstood.[82] Two cylinders of each earthen mortar/E-330 combination were tested.

Wetting/Drying – Cylinders of soil were soaked in ambient temperature tap water for five hours, and then oven-dried overnight at approximately 90° C. The condition and weight of the soil cylinders was noted at the end of each drying cycle. ASTM Standard D559 is the basis for this

80 "D1635, Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading", (Philadelphia: ASTM, 1993).

81 James R. Clifton, "Adobe I: The Properties of Adobe" *Studies in Conservation* 23 (1978): 142.

82 "D560, Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures", (Philadelphia: ASTM, 1993).

test.[83] Two cylinders of each soil/E-330 combination were tested, as well as two cylinders of all soil/Rhoplex combinations (except Chaco Canyon BLM Quarry) dried at approximately 40°F, and two cylinders of Mesa Verde Blend 25% mortar frozen, then dried at ambient conditions.

Scanning Electron Microscopy – Earthen mortar samples were observed using secondary electron imaging with a JEOL JSM-6300FV Scanning Electron Microscope (SEM). Primary electrons from the microscope's electron beam strike the surface of the sample, and secondary electrons are ejected. Secondary electron imaging is valuable for revealing surface characteristics because secondary electrons are topographically sensitive, and can provide high spatial resolution.[84] These electrons carry little information about the elemental composition of the sample, but the reason for scanning the earthen mortar samples was to reveal the micromorphology of the Rhoplex/soil system.

The earthen mortar samples were mounted on a carbon disk using conductive carbon paint. Two to four samples, each with a freshly broken edge facing up, were fixed on a disk, and coated lightly with conductive carbon, a standard SEM preparation to prevent the buildup of electrical charges on the sample during observation.

Laboratory samples of unamended earthen mortars and mortars containing E-330 were scanned, as well as field specimens from ruins, and mortar and adobe samples from early E-330 trials.

Color – The color of earthen mortar samples was determined in the same manner as loose soil. For this characterization, the water vapor transmission mortar disks were used. One sample of each soil and Rhoplex concentration was subjected to Munsell color matching. Two color matches were recorded, dry and damp.

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83 "D559, Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures", (Philadelphia: ASTM, 1993).

84 *Energy-Dispersive X-Ray Microanalysis: An Introduction* (San Carlos, CA: Kevex Instruments, 1989), 6-7.

4.2.2 Earthen Mortar Sample Preparation

Cylinders (1.5" d x 1.5" h) of earthen mortar were cast for both the wetting/drying test and the freezing/thawing test. Disks (3.5" d x 0.75" h) were cast for the water vapor transmission test, and prisms (0.75" w x 0.75" h x 4.25" l) were cast for the modulus of rupture test. The molds for the cylinders for the wetting/drying test and the freeze/thaw test were made from sections of PVC pipe with an inside diameter of 1.5". The water vapor transmission (WVT) disks were cast in Plexiglas molds. The prisms for the modulus of rupture test were cast in special wooden molds built for these tests. The molds could be disassembled so that the prisms could be removed without damage. All the molds were lightly lubricated with petroleum jelly so the samples could be removed intact. Typical laboratory conditions were 65°F and 35% relative humidity. Samples cast in the PVC molds were removed as soon as they dried enough to pull away from the side of the mold, usually overnight. Samples in the wooden molds also were left to dry overnight before they were removed from the molds. The samples were then air-dried on a wire rack in the laboratory for at least eleven days before testing.

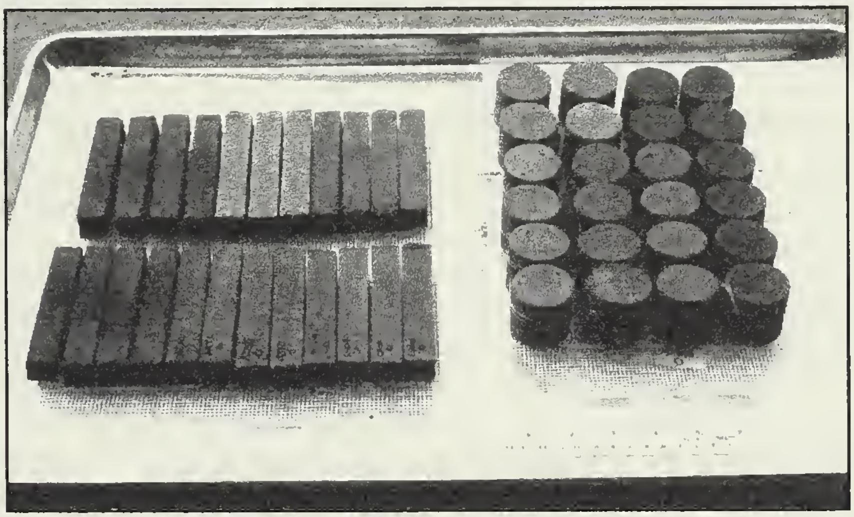

Figure 9. This tray holds a fraction of the 290 earthen mortar samples made for the physical tests. The cylinders were used for the wetting/drying and freezing/thawing tests. The rectangular prisms were used for the modulus of rupture (bending) test. Not shown are the disks used for the WVT test. The samples were dried and stored in the laboratory before testing.

A few of the samples were dried in a refrigerator at approximately 40°F, below the 50°F glass transition temperature of E-330. This proved more difficult in practice than in theory. The small size of the refrigerator, coupled with the lack of air movement and the relatively poor water adsorption capacity of cold air meant that the samples took days to dry. Ice build-up on the thermocouple controlling the thermostat caused the temperature in the back of the refrigerator to dip below 32°F, freezing some of the modulus of rupture prisms. This was recorded in the lab notes, and those prisms were recast. Some of the frozen samples were tested, and the results are reported in the appropriate section of this report. The refrigerator was defrosted after this occurrence and the samples were placed in closed plastic containers containing a calcium sulfate desiccant and replaced in the refrigerator. The desiccant was changed daily. Samples were removed from the refrigerator when a representative sample, weighed daily, stopped losing weight. They were then stored at ambient laboratory conditions for at least two weeks until tested.

The following concentrations of E-330 and water were chosen for the physical tests. A 6% Rhoplex E-330 mix represents 6 ml of E-330 (47% solids) in 94 ml of deionized water, to make 100 ml total.

RHOPLEX E-330 CONCENTRATION IN EARTHEN MORTAR

Percent E-330 (47% solids) in Water for Mortar Mix	Approximate Equivalent Ratio E-330:H_20 (parts by volume)
0%	0:1
6%	1:17
12.5%	1:7
25%	1:3
33%	1:2

Table 5

These concentrations represent the full range of field conditions. Most field applications are probably in the range of 1:3 and 1:2, E-330 to water. Fenn recommended a concentration of approximately 1:2.5.

The amount of water needed to make a workable mix varied with each soil. Clifton proposed that every adobe soil has an optimum water content that provides maximum performance.[85] The amount of water (and water and E-330 mixture) added to the dry soil used to make the prisms and cylinders was the amount needed to bring the soil to a point between its plastic limit and liquid limit. If that amount of liquid did not result in a workable mix, the proportions were changed until a workable mix was obtained. The definition of "workable mix" is a mixture of soil and water and Rhoplex that could be worked with a plastic spatula into the corners and edges of the molds, but still providing some resistance. This is admittedly a subjective measure, in the lab as well as in the field. The amount of moisture in the sample was calculated by oven-drying a sample and recording the weight lost as a percent of water in the mix. In practice, the amount turned out to be near the liquid limit for the two soils with higher percentages of clay, Mesa Verde Blend and Chaco Canyon BLM Quarry. The two sandier soils, Aztec Ruins Blend and New Mexico Alcalde Adobe required liquid near their plastic limit. (This can only be an approximation for the adobe soil, since it was too sandy for liquid or plastic limit determination.)

The total amount of soil and liquid was recorded for each sample preparation, so the amount of polymer solids in each sample could be calculated. An interesting difference was revealed between the two soils with a higher clay percentage and the two sandier soils. Since the soils with a higher percentage of clay and silt needed more liquid to make a workable mix, they were also higher in total polymer solids. Once a formula was found for a workable mix, it was used for the succeeding mortar sample preparations. Since the fluid mixture at higher E-330 levels contained more solid polymer and less water as the proportions increased, the mixes became slightly drier at the proportions increased. The following table shows the percent water used to make the mortar samples, and the resulting percent acrylic solids, by weight and volume, in the mortar samples.[86]

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85 James R. Clifton, *Preservation of Historic Adobe Structures – A Status Report* (Washington: National Bureau of Standards, 1977), 4.

86 Assuming the density of E-330 to be 1.0 g/cm^3 and soil to be 2.65 /cm^3.

EARTHEN MORTAR SAMPLES
PERCENT WATER AND PERCENT ACRYLIC SOLIDS

Soil	Percent E-330	Water in Mortar Mix (percent of wet weight)	Percent E-330 solids in Mortar Sample (by weight)	Percent E-330 solids in Mortar Sample (by volume)
Aztec Ruins Blend	0%	(not determined)	0%	0%
Chaco Canyon BLM Quarry	0%	(not determined)	0%	0%
Mesa Verde Blend	0%	21%	0%	0%
New Mexico Alcalde Adobe	0%	17%	0%	0%
Aztec Ruins Blend	6%	15%	0.5%	1%
Chaco Canyon BLM Quarry	6%	19%	0.6%	1%
Mesa Verde Blend	6%	20%	0.6%	1%
New Mexico Alcalde Adobe	6%	16%	0.6%	1%
Aztec Ruins Blend	12.5%	16%	1.1%	3%
Chaco Canyon BLM Quarry	12.5%	20%	1.3%	3%
Mesa Verde Blend	12.5%	20%	1.5%	4%
New Mexico Alcalde Adobe	12.5%	15%	1.2%	3%
Aztec Ruins Blend	25%	15%	2.0%	5%
Chaco Canyon BLM Quarry	25%	21%	2.6%	7%
Mesa Verde Blend	25%	21%	2.9%	8%
New Mexico Alcalde Adobe	25%	14%	2.1%	6%
Aztec Ruins Blend	33%	14%	2.8%	7%
Chaco Canyon BLM Quarry	33%	21%	3.4%	9%
Mesa Verde Blend	33%	20%	3.9%	10%
New Mexico Alcalde Adobe	33%	13%	2.8%	7%

Table 6

Table 6 reveals that soils with higher percentages of fine particles, particularly clay, take more liquid, proportionally, to make a workable mortar than soils containing higher percentages of sand. In practice, this means that even though the proportions of water and E-330 are blended precisely to achieve the desired E-330 solids concentration in the liquid component of the mortar mix, the final E-330 percentage in the earthen mortar mix will vary from soil to soil, with high-clay earthen mortars ending up with higher proportion of polymer. For example, the Mesa Verde Blend earthen mortar samples, made with 33% E-330 in water, had 10% polymer solids, by volume, while the New Mexico Alcalde Adobe earthen mortars had only 7% polymer solids.

When comparing the behavior of two different soils amended with Rhoplex E-330 (or any other water-based amendment) it is not enough to know the ratio of water to amendment. It also is important to know the total amount of liquid used, and the amount of soil, in order to accurately calculate how much amendment, by weight or volume, remains in the amended soil. In this research, for example, the New Mexico Alcalde Adobe mortar, mixed with 33% E-330 in water, actually had less residual polymer (2.8%) than did the Mesa Verde Blend mortar at 25% (2.9%).

5
DATA

5.1 Soil Characterization

The soil characterization summaries in Appendix B provide all the results available from the soil tests. On these sheets (one for each soil) the particle size distribution information is presented on a semi-log graph, charting percent passing vs. particle size. The particle size distribution pie chart in each summary divides the soil into four categories (coarse sand, fine sand, silt and clay) using the ASTM particle size classification system. Appendix C provides the same information, organized by characterization feature. The results of the characterization tests for the four soils and soil blends tested as earthen mortars in this report are provided in tables or graphs in this section.

Color – Mesa Verde Red was a rich red-brown, and Mesa Verde Yellow was yellow-brown. The Hovenweep soils were red and pink. Both Hovenweep Pink and Mesa Verde Yellow probably owe part of their light Value to their high carbonate content. The Chimney Rock soils were yellowish brown, and the Aztec Ruins soil components were all pale brown or brown. The Chaco Canyon soils likewise were shades of brown. The very sandy New Mexico Alcalde adobe soil was pale brown. A complete chart of the Munsell colors of soils characterized in this report appears in Appendix C.

MUNSELL SOIL COLORS

Soil	Dry Color		Moist Color	
Mesa Verde Blend	7.5YR 5/4	brown	7.5YR 3.5/5	strong brown
Aztec Ruins Blend	10YR 5.5/3	pale brown/brown	10YR 3/3	dark brown
Chaco BLM Quarry	10YR 4.5/3	brown/dark brown	10YR 4/3.5	dark brown/dark yellowish brown
New Mexico Alcalde Adobe	10YR 6/3	pale brown	10YR 4/3	brown/dark brown

Table 7

Particle Size Distribution – The soils varied widely in their particle size distribution, from almost all sand to predominately clay. The following bar graph summarizes the information about particle size distribution for the four soils or soil blends used as mortars in this research, determined by sieving and by the sedimentation method.

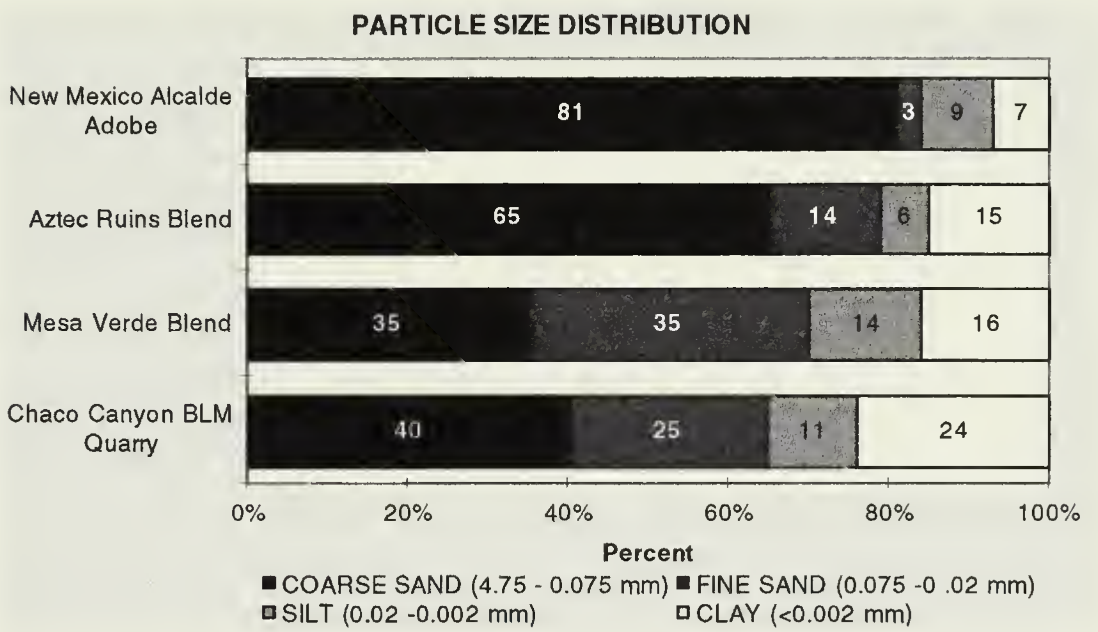

Figure 10. Particle Size Distribution of mortar soils

Soil Particle Description – The fraction of the Southwestern soils in the range of 2.36 mm to 0.075 mm (coarse sand) was observed with a low-power binocular microscope, and information

about particle size distribution, particle shape, color, organic material and other distinguishing characteristics was noted. The table following summarizes the data for the four soils tested as earthen mortars.

PARTICLE DESCRIPTION OF FOUR EARTHEN MORTAR SOILS
(Particles > 0.075 mm)

Soil	Particle Size	Particle Shape	Color	Other Characteristics
Aztec Ruins Blend*	Particles fairly evenly distributed throughout the coarse sand range	Angular, predominately low-to-medium sphericity	Predominately white, quartz-like; few black, yellow grains	Trace of fine woody fibers
Chaco Canyon BLM Quarry	25% in the range 0.150-0.300 mm, 75% in the range 0.075-0.150 mm	Angular, medium-to-high sphericity	Predominately yellowish-white, quartz-like; few black, gray grains	Trace of woody fibers
Mesa Verde Blend*	Grains distributed throughout the coarse sand range, but concentrated between 0.075 and 0.300 mm	Angular, low-to-medium sphericity	Predominately white, quartz-like; particles from Mesa Verde Yellow coated with yellow-orange calcite	Trace of woody fibers; calcite is visible in all size ranges
New Mexico Alcalde Adobe	A fine sandy soil, more than 50% of the grains are in the range of 0.075-0.300 mm	Angular, low-to-medium sphericity	Predominately white, quartz-like; some pink and orange grains	No significant organic material; flat, brown, transparent plates in the finest fraction; some calcite in the larger size ranges

*See individual Soil Characterization Sheets in Appendix B for soil component data

Table 8

The complete soil particle description for each soil is included on the individual Soil Characterization Sheets in Appendix B.

Soil Density – The density of soils tested for this report ranged from 2.60 to 2.75 g/cm^3. The soil density was used in the calculation of particle size distribution by the sedimentation method. A list of the calculated soil density values for all soils is summarized in Appendix C. The densities of the four mortar soils were calculated as follows: Aztec Ruins Blend, 2.66 g/cm^3; Chaco Canyon BLM Quarry, 2.67 g/cm^3; Mesa Verde Bland, 2.70 g/cm^3; and New Mexico Alcalde Adobe, 2.69 g/cm^3.

Qualitative Soluble Salt Analysis – None of the soils tested positive for chlorides, sulfates, nitrates or phosphates. A table of microchemical tests used for the determination of the presence of significant soluble salts, *Qualitative Test for Anions*, is included in Appendix C.

Acid-Soluble (Carbonate) Content – Most of the Southwestern soils had measurable levels of acid-soluble materials, presumably calcium carbonate, typical of soils in this area. Three soils, both Chimney Rock soils and Aztec Ruins Sand, did not show a positive indication of carbonates when tested with a drop of acid, and were not tested further. The remaining 14 soils were subjected to the complete test. Twelve ranged between 2.2% and 8.1%. The two remaining soils, Mesa Verde Yellow and Hovenweep Pink, had much higher carbonate levels, 22.6% and 21.3% respectively. The results for the four soils tested as earthen mortars are shown below. The acid-soluble test results for all of the Southwestern soils tested are included in Appendix C.

ACID-SOLUBLE (CARBONATE) CONTENT

Soil	Percent Acid-Soluble
Mesa Verde Blend	8.1%
Aztec Ruins Blend	2.4%
Chaco Canyon BLM Quarry	3.8%
New Mexico Alcalde Adobe	3.9%

Table 9

pH – The pH of the Southwestern soils in water fell within a range of 6.9 to 8.3. Excluding the Chimney Rock soils, the range was 7.5 to 8.3, slightly alkaline. Rhoplex is manufactured for use in concrete, a highly alkaline environment. Because nearly all the soils proved to be slightly alkaline there is no reason to believe that the pH of the soils would interfere with the film formation of the emulsion. The pH measurements of all the characterized soils are included in Appendix C.

MORTAR SOIL pH

Soil	pH in Water	pH in $CaCl_2$
Mesa Verde Blend	7.7	7.5
Aztec Ruins Blend	7.6-7.7	7.3
Chaco Canyon BLM Quarry	8.2	7.8
New Mexico Alcalde Adobe	7.6-7.7	7.3

Table 10

At least one author suggests that each adobe soil has an optimum pH, and that adjustment of the pH by the judicious addition of buffers might bring about an improvement in performance.[87] But no research on this subject was discovered.

Atterberg Limits – Two of the four soils used in the earthen mortar tests, Chaco Canyon BLM Quarry and New Mexico Alcalde Adobe, had indeterminate plastic limits; the soils split before a 3.2 mm cylinder could be formed. Surprisingly, Aztec Ruins Blend proved to have a larger plasticity index (LL-PL) than Mesa Verde Blend. This is contrary to the general assumption that a higher plasticity index means a greater tendency to expand and contract upon wetting and drying, and display greater strength as the plasticity index increase.[88] The Aztec soil showed less shrinkage than the Mesa Verde soil. The coefficients of activity for all the soils characterized were from 0.1 to 0.5, well within the "inactive" range (<0.75). The Atterberg limits for the soils tested as earthen mortars are shown in the following table. The Atterberg limits for all of the Southwestern soils are included in Appendix C.

[87] Thomas T. Eyre, "The Physical Properties of Adobe Used as a Building Material" *The University of New Mexico Bulletin, Engineering Series* 1, no. 3 (1935): 30-31.
[88] Teutonico, 106.

ATTERBERG LIMITS

Soil	Plastic Limit	Liquid Limit	Plasticity Index
Mesa Verde Blend	19.2	21.9	2.7
Aztec Ruins Blend	16.7	23.8	7.1
Chaco Canyon BLM Quarry	Indeterminate	19.5	NP**
New Mexico Alcalde Adobe	Indeterminate	Indeterminate	NP*

NP* = non-plastic, no liquid limit, so plastic limit not attempted
NP** = non-plastic, soil broke before 3.2 mm cylinder could be formed

Table 11

Shrinkage (Linear and Volumetric) – Shrinkage was another area where the soils displayed great variation. As expected, high sand content soils had little shrinkage, while soils with higher clay levels shrank more. The following chart shows the linear and volumetric shrinkage for the four earthen mortar soils. Appendixes B and C provide the shrinkage data for all soils.

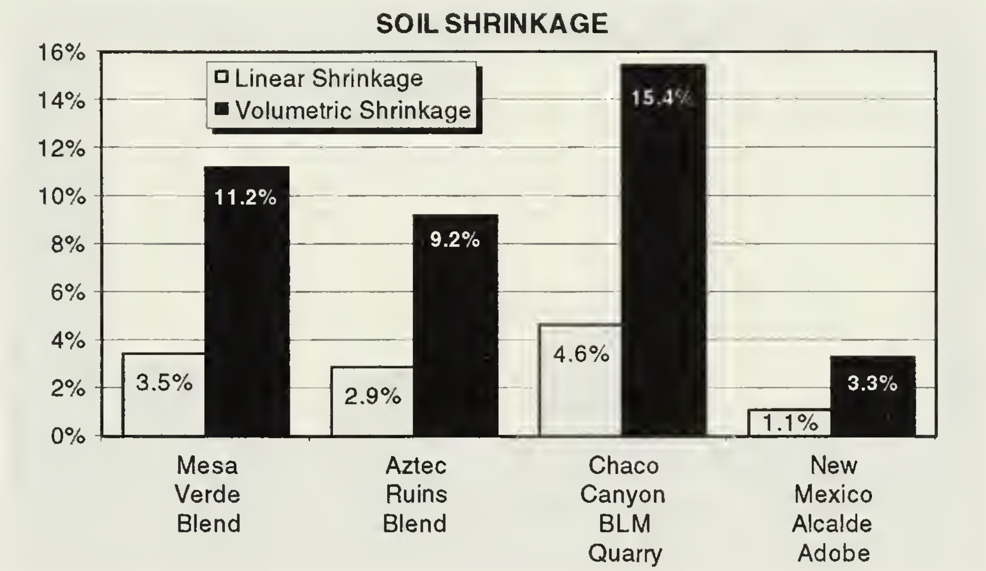

Figure 11

X-Ray Diffraction – The three soils used for mortar repairs at the parks and monument – Mesa Verde Blend, Aztec Ruins Blend, and Chaco Canyon BLM Quarry – plus Chaco Canyon South Gap soil, were submitted for x-ray diffraction analysis.[89]

The XRD results confirmed the findings of the visual characterization and physical testing of the subject soils. Quartz was the dominate mineral in all of the samples submitted for XRD analysis, followed by clay minerals, feldspar, and some calcite and dolomite. Of the clay-size minerals (≤2µm) kaolinite, a relatively dimensionally stable clay, was predominate in all of the analyzed soils. Illite, a moderately stable clay, was a distant second, but present in all the clay-size fractions. Dimensionally unstable smectite and/or mixed illite/smectite were present (at least one part in ten) in all of the soils except one.

The XRD results correlate with the soil shrinkage data. Of the three soils currently used for mortar repairs, the soil with the greatest proportion of dimensionally unstable clay, Chaco Canyon BLM Quarry, also exhibited the greatest shrinkage. Chaco Canyon South Gap soil, which exhibited virtually no linear shrinkage (0.35%) had the highest percentage kaolinite, no smectite and only a trace of mixed illite/smectite.

Besides the clay minerals, all the soils had traces of other minerals in the <2µm fraction, primarily quartz, but also traces of calcite and dolomite. Complete XRD results are included in *Table 12*.

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89 XRD analysis was performed by the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

MINERALOGY OF MORTAR SOIL CLAY-SIZE (< 2μm) FRACTION*

Soil	Kaolinite	Illite	Smectite	Mixed Illite/Smectite	Other Minerals**
Aztec Ruins Blend	8	1	1	-	quartz (minor) calcite (minor)
Chaco Canyon BLM Quarry	7	1	1	1	quartz (major)
Chaco Canyon South Gap	9	1		trace	quartz (major)
Mesa Verde Blend	7	2	1	-	quartz (major) calcite (minor) dolomite (minor)

* Clay minerals reported as parts in ten
** Major or minor trace minerals other than clays

Table 12

Bulk Mineralogy – Analysis of a complete sample of each of the three National Park Service mortar soils – Mesa Verde Blend, Aztec Ruins Blend, and Chaco Canyon BLM Quarry – plus Chaco Canyon South Gap soil, showed them to be predominately quartz (SiO_2).[90] The other minerals, present in much smaller quantities, are listed in *Table 13.*

The most successful E-330-amended mortar soil of the group, Chaco Canyon Sough Gap (still in place 20 years after its installation in test walls at Chaco Canyon), is the least complex mineralogically, predominately quartz, with minor amount of feldspars and clay. All the other soils, and particularly Mesa Verde Blend, reveal measurable traces of carbonates. (For comparison, the acid-soluble fraction of these soils as determined in the laboratory also is listed in *Table 13.*) What effect, if any, the carbonates might have on durability of soils when used as amended earthen mortars is unclear. The limited solubility and mobility of the minerals in a frequent wetting/drying situation potentially could affect the soil-polymer bond.

90 Bulk mineralogical analysis was performed by the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

BULK MINERALOGY OF MORTAR SOILS

Soil	Dominant Mineral	Other Minerals*	Acid-Soluble Fraction
Aztec Ruins Blend	quartz	orthoclase feldspar dolomite plagioclase feldspar calcite clay minerals	2.4%
Chaco Canyon BLM Quarry	quartz	plagioclase feldspar orthoclase feldspar clay minerals calcite	3.8%
Chaco Canyon South Gap	quartz	plagioclase feldspar orthoclase feldspar clay minerals	2.2%
Mesa Verde Blend	quartz	plagioclase feldspar calcite dolomite clay minerals	8.1%

* Listed in order of abundance

Table 13

5.2 Earthen Mortar Sample Testing

Water Vapor Transmission – All the earthen mortar samples were porous and permeable; some lost almost 1g of water a day through a 0.75" thick soil disk with a diameter of approximately 2.75". In Appendix D, the water vapor transmission (WVT) data is presented so that earthen mortars of various percentages of E-330 can be compared to other samples of the same soil type, and to different soils with the same concentration of E-330.

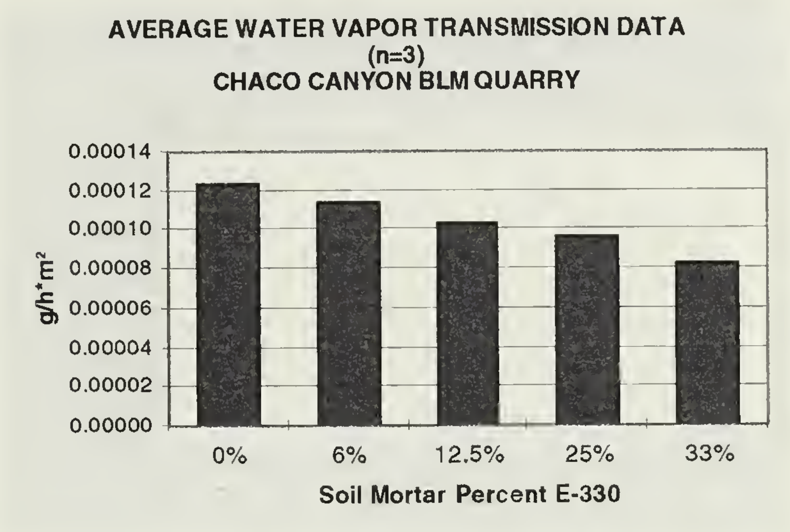

Figure 12. With increasing amounts of Rhoplex E-330 in the Chaco Canyon BLM Quarry earthen mortar samples, the ability to transmit water vapor was impaired. The vertical axis of the graph is water vapor passing through the sample in grams/hour·m^2. This performance was typical of the amended soils; more E-330, less permeability.

As anticipated, the WVT rate decreased as the amount of polymer in the sample increased. Two slight anomalies were recorded in the Aztec Ruins data and the New Mexico adobe soil. In each case one set of earthen mortar samples did not follow the expected trend. More than likely, however, these differences were due to inconsistencies of the soil samples.

From the most permeable to least permeable, the soils almost always arranged themselves in the following order: New Mexico Alcalde Adobe, Mesa Verde Blend, Chaco Canyon Quarry and Aztec Ruins Blend. The single exception was found in the unamended earthen mortar samples, where the Mesa Verde Soil was found to be the most permeable. This anomalous result may be experimental error, unless the addition of a small amount of acrylic polymer makes some sandy soils more permeable.

All of the graphical results in the Appendix D compare the WVT rate in grams of water transmitted per hour per unit area. In tabular form, the derived rates of permeance and permeability, also are presented.

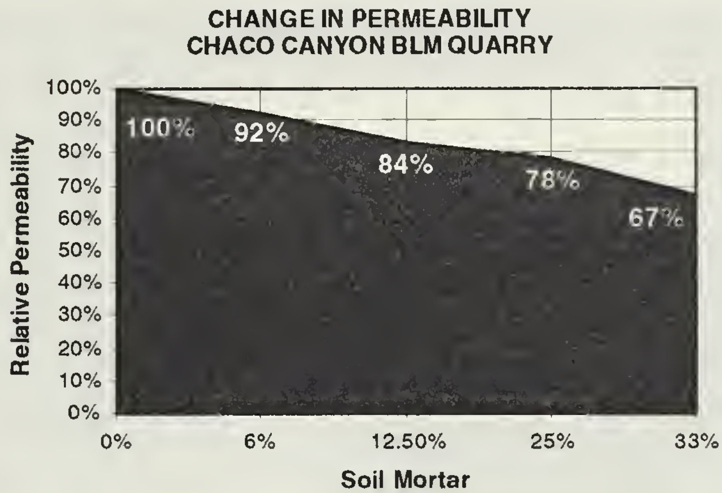

Figure 13. Assuming the unamended (0% E-330) Chaco Canyon BLM Quarry earthen mortar sample is as permeable as this soil ever is, this graph compares the relative permeability of the amended samples of the same soil. In this example, the 33% E-330 sample is only 67% as permeable as the unamended sample.

Three disks of each earthen mortar/Rhoplex combination were tested. The large number of test assemblies required three test chambers. All samples were tested simultaneously. After five days, the control disk assemblies (without water) reached equilibrium, and the WVT test began. From this point, 43 days of test readings were recorded. WVT, permeance and permeability calculations were based on the arithmetic mean of each set of three disks. No other statistical analysis was performed.

Modulus of Rupture – An Instron 1331 Testing Machine was used for the modulus of rupture test. Stroke speed was set at 0.043 inches/minute, and a ball bearing device below the load cell helped accommodate the irregularities in earthen mortar samples. The results of this test are summarized in this section; more complete information is presented in Appendix D.

Increasing the amount of E-330 increased the amount of force needed to break the earthen mortar prisms. Only a single sample, 6% E-330 Aztec Ruins Blend, did not follow this direct relationship. For an unknown reason, these samples were almost twice as strong as the testing experience would have predicted. Perhaps the samples were particularly well made, with no large grains, voids or other areas of weakness cast in the prisms.

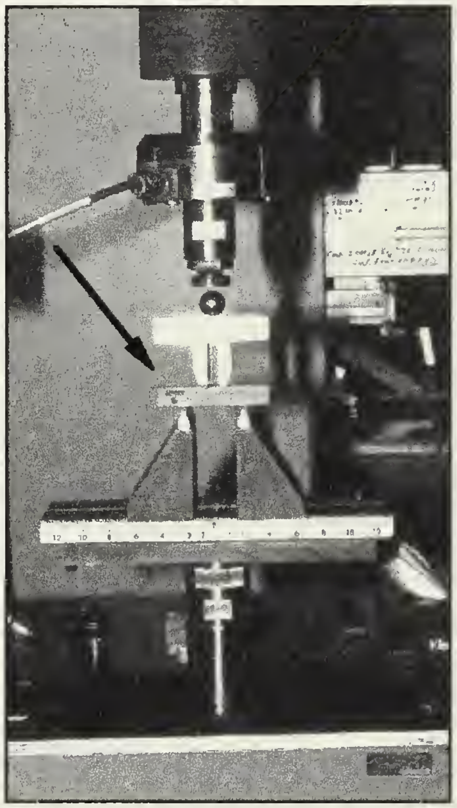

Figure 14. The modulus of rupture, or four-point bending, test was performed on an Instron Testing Machine. The earthen mortar prism is indicated by the arrow. The device measured the amount of force, applied from the top, it took to break the soil sample, as well as the amount of deflection before the break occurred.

Overall, the Chaco Canyon earthen mortars were the strongest, amended or unamended. The Mesa Verde Blend samples benefited most from the addition of E-330, as measured by strength in bending. The soil was more than four times stronger at the 33% level, compared to an unamended sample. The Chaco Canyon soils showed the least percentage increase in strength. The weakest soil, amended or unamended, was the New Mexico Alcalde Adobe soil.

There seemed to be no significant difference in strength between earthen mortar samples dried at 40°F and those dried at ambient laboratory conditions. The cold-dried Chaco Canyon BLM Quarry samples at 25% and 33% E-330 were the strongest earthen mortar samples tested, requiring over 500 pounds/in^2 to break the small prisms. The samples frozen and then dried at ambient conditions performed poorly, probably because of the cracks formed by expanding water during the

freezing process which never closed during the ambient drying. The bending test is particularly sensitive to cracked samples.

Since the Instron recording equipment also recorded the displacement of the sample before it broke, the ratio of the force required to break the sample, in pounds/in^2, and the displacement, in inches, was calculated and graphed. The result was a measure of brittleness, or how far the sample prisms deflected before they failed. Two of the soils, Aztec Ruins Blend and the Chaco Canyon BLM Quarry, became more brittle as the amount of E-330 increased. One soil, Mesa Verde Blend, showed no change in brittleness. The fourth soil, the New Mexico adobe soil, showed a decrease in brittleness as the amount of polymer increased. Low temperature drying (40°F) seemed to have no effect on this characteristic.

This is a curious finding. The two sandiest soils, New Mexico Alcalde Adobe and Aztec Ruins Blend, reacted oppositely. The very sandy adobe soil became less brittle, while the more richly textured, but still sandy, Aztec soil became more brittle. Because the adobe soil is almost all sand (81%), held together with only 7% clay, it is reasonable that the addition of a flexible, adhesive polymer would make the soil less brittle. Why the Aztec soil, or for that matter all the other soils, did not become less brittle is unknown. There are many variables – clay type and percentage, soil porosity, particle size distribution, carbonate content, etc. – that could affect this property of amended soil. The limited testing of this research did not provide definitive answers to this question.

Four sample prisms of each earthen mortar/Rhoplex combination were prepared for testing. The arithmetic mean of the test results for each set of four was used to calculate the modulus of rupture. The standard deviation also was calculated. This data is presented in Appendix D.

Wetting/Drying – The wetting/drying test of half the samples was interrupted after 10 cycles when the drying oven in the laboratory failed. When the test resumed, some samples were replaced with new samples, and some of the first set were carried over. Some samples underwent

only seven cycles of wetting and drying, and some underwent 17 cycles. In 17 cycles (or less) nine samples containing Rhoplex E-330 failed the test, as defined by losing 5% or more of dry weight. (All of the unamended earthen mortar samples failed completely during the first immersion.) It is certain that if the test had been continued to 20 or 30 cycles more samples would have failed, because fatal cracks had begun to appear in some of the earthen mortar samples. The results of the wetting and drying test are presented in a table in Appendix D.

This is a very aggressive test, and not entirely like the field conditions the mortars experience in the ruins, where wetting and drying occur more gradually. But wetting and drying, sometimes combined with freezing temperatures, are exactly what the exposed mortar is asked to survive. It is a severe test of E-330 because of the expansion and contraction of some of the soils. The types of failures observed in the field, particularly at Mesa Verde, were observed in some of the wetting/drying earthen mortar samples.

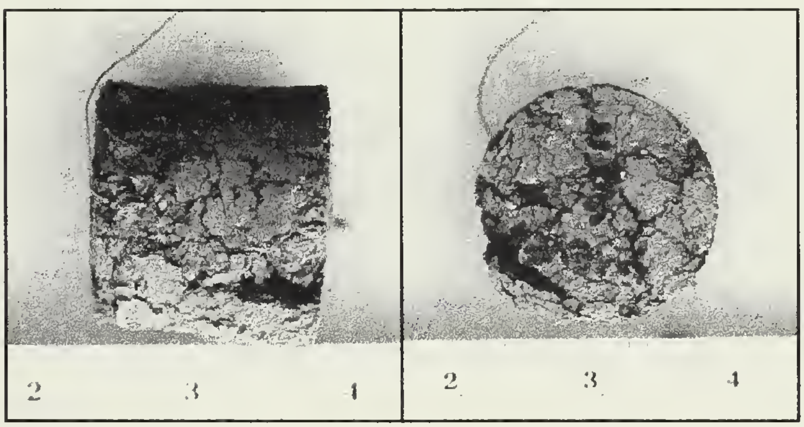

Figure 15. Flaking deterioration of this acrylic emulsion-modified Mesa Verde Blend earthen mortar cylinder can be seen in these photographs. The sample, modified with 6% E-330, had undergone 17 cycles of wetting and drying A similar phenomenon was observed in the field.

The New Mexico adobe soil did not exhibit the cracking observed on the other three soils. Through ten cycles, the New Mexico adobe soil samples amended with 6% E-330 were still essentially unchanged. Through seven cycles, all other amended New Mexico adobe soil samples, but one, had lost less than 1% by weight. That one, a cold-dried sample, had granular loss of 1.2%.

The Aztec Ruins earthen mortar samples at 6% E-330 survived 10 cycles with less than 1% loss, and all the other amended samples survived seven cycles. The 12.5% and 25% samples showed slight, fine, cracking on the sides of the cylinders. The 33% samples did not exhibit this cracking.

The Chaco Canyon BLM Quarry earthen mortars demonstrated more activity, and more deterioration, than the sandier Aztec Ruins and New Mexico adobe soils. The 6% E-330 samples lost nearly half their weight after seven cycles, and a 12.5% sample lost 21% of its weight after 17 cycles. The 25% samples were cracking on the sides at the end of seven cycles, and the 33% samples were also cracking, although not as badly.

The wetting and drying test of the Mesa Verde Blend samples revealed the same fine flaking and contour scaling seen at the ruins in Colorado. All of the 6% samples failed the wetting and drying test. The 12.5% and 25% samples subjected to 17 cycles both lost more than 1% of their weight, and the 12.5% sample was exhibiting flaking, fine cracks and contour scaling, certain symptoms of future failure. Though performance seemed to improve as the amount of E-330 increased, even the 33% sample subjected to 17 cycles began to exhibit the fine cracking and flaking typical of Mesa Verde mortar failure.

Weight loss is an objective measure of mortar performance, but appearance, including fine or gross cracking and flaking, is a subjective measure of performance. Some samples that had not lost more than 1% of their weight, could still be judged failures because of surface cracking. Cracking opens more channels for water entry, potentially setting up future failure as water gains access to the interior of the mortar, causing damage by swelling soils and by freezing and thawing.

Figure 16. The wetting/drying test was the most challenging of the mortar tests. The samples were alternately soaked for five hours in room temperature water, and then dried in a warm oven, one cycle per day. The badly deteriorated samples in this tray are 6% Mesa Verde Blend earthen mortars, after 7 cycles.

No difference in performance was noticed between samples dried at laboratory conditions and samples dried at 40°F. Two Mesa Verde 25% samples frozen and then dried in the laboratory at ambient conditions, performed as well as similar unfrozen samples, although they exhibited fine vertical cracking unique to the frozen samples, cracks that probably are seeds of future destruction.

No statistical analysis was performed on the data from this test.

Freezing/Thawing – The freezing/thawing test concluded after 17 cycles. Half of the samples remained in the freezer for four additional months, and half were removed to the laboratory, to dry at ambient conditions. The freezer remained between –5°F and –10°F for most of the test. This

test was a disappointing attempt to modify an ASTM test for compacted soil-cements. The data were restricted to visual observations and gross physical measurements of cylinder dimensions. Because the samples never dried, and were soft and fragile when wet, measurements such as weight loss and resistance to abrasion were not possible. Nevertheless, the data derived from the freezing/thawing test are useful.

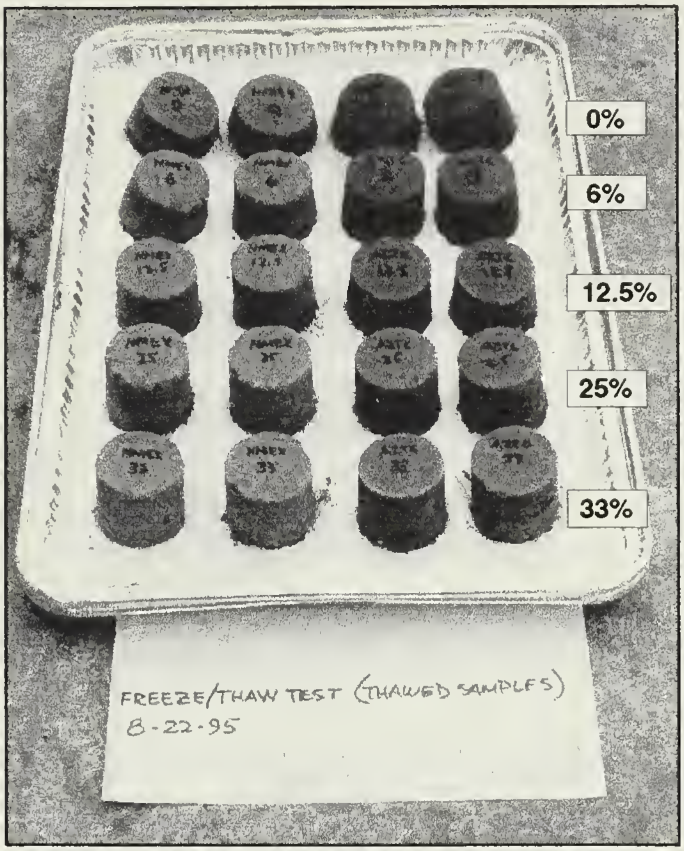

Figure 17. After 17 cycles of freezing and thawing, these mortar samples have been air-dried in the laboratory. The two columns of cylinders on the left are New Mexico Alcalde Adobe earthen mortar, and the two on the right, Aztec Ruins Blend. The row labels show the amount of E-330 in the mortar sample. The less Rhoplex in the mortar, the more the cylinders slumped. The 33% samples hardly changed in shape during the test. Compare these samples with the higher clay content soils, Mesa Verde Blend and Chaco Canyon BLM Quarry (**Figure 18**).

All of the samples changed shape as they became saturated with water, but the addition of E-330 resulted in the stabilization of shape; the more E-330, the greater the stabilization. A significant difference in shape change between the essentially sandy earthen mortars and the earthen mortars higher in clay and silt content was observed, and graphed. The sandier soils, New Mexico adobe and Aztec Ruins, slumped, becoming shorter and wider. The two other soils swelled, maintaining height and becoming wider.

Gross cracking was observed on the top of the Mesa Verde and Chaco Canyon samples, particularly in the 0% and 25% samples, but also the other E-330 proportions. These two soils showed

the least gross cracking at the 12.5% and 33% percentages. Very little gross cracking occurred with the other two soils. The tops of the 6% Aztec Ruins Blend cylinders showed some slight cracking. The New Mexico adobe soil did not crack.

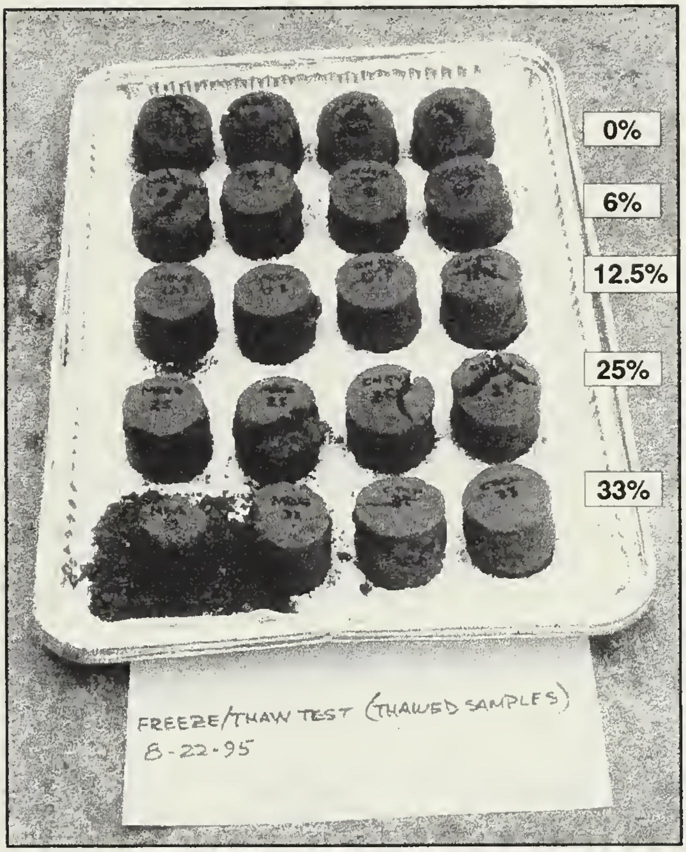

Figure 18. These air-dried mortar samples were subjected to 17 cycles of freezing and thawing. The two columns of cylinders on the left are Mesa Verde Blend earthen mortar, and the two on the right, Chaco Canyon BLM Quarry. The row labels indicate the amount of E-330 in the mortar samples . Notice how badly these earthen mortar samples have slumped and swollen. All the samples displayed dimensional instability, and some cracked badly on the top. The severe flaking of the 33% Mesa Verde sample (lower left) is probably due to "freeze-drying", dehydration of the swollen, saturated soil in the freezer over a three-month period. When it thawed, the top, or crown, of the sample sloughed off. Other samples also were deteriorated in this area.

An interesting phenomenon was observed when the samples kept in the freezer during the summer were removed. As the tray of frozen samples was placed on a laboratory table, the top of the 33% Mesa Verde Blend sample began to crumble around the edge in fine fragments. When probed with a pair of tweezers, the frozen soil was soft and crumbly on the surface. The phenomenon was also observed on the other frozen samples, but it was most prominent on the Mesa Verde Blend samples.

Even after these samples were warm and dry, they retained a light discoloration on the top edges, with the amount of discoloration proportional to the amount to E-330 in the mix. The discolored area on all samples was softer, less resistant to probing. The effect was probably produced by freeze drying, when the

saturated, swollen soils were dehydrated in the freezer. The higher percent E-330 soils probably absorbed less water, and dried more rapidly, causing more discoloration. This phenomenon was most noticeable on the two soils highest in clay content, Mesa Verde Blend and Chaco Canyon BLM Quarry.

The dry samples removed from the freezer and placed in the lab in May did not exhibit the same disintegration. However it was found that the small flakes on the surface of the 6% Mesa Verde sample were not well attached, and fell off when gently probed. No other earthen mortar samples showed fine cracking. The 33% and 25% Mesa Verde samples showed some flaking, more on the 33% sample. The probe revealed that these flakes were not well attached. Overall, though, the probe revealed that the samples were still sound, and the more E-330 the sample contained, the more resistant they were to probing.

The dry freezing/thawing samples were compared to wetting/drying samples, and it was discovered that the wetting/drying samples were harder, as measured subjectively with the pick test. Even though the wetting/drying samples were more severely cracked on their surfaces, the cracked sections and flakes were more securely attached to the body of the cylinder. The freeze/thaw samples had rougher surfaces, and were easier to abrade with finger pressure, at all E-330 concentrations.

No statistical analysis was performed on the data from this test.

Color – The addition of Rhoplex E-330 to the Southwestern soils changed the color of the soils subtly, when compared to loose, unamended soils. One of the advantages of an acrylic amendment is the minimal effect the amendment has on the earthen mortar color. The colors were almost always within 0.5 or 1.0 of the loose soil in value and/or chroma. Most of the dry mortar samples were slightly darker, and most of the moist mortar samples were slightly lighter. Paradoxically, the Chaco Canyon soil was slightly lighter dry, slightly darker moist. The lightening

of the moist mortar samples is probably because the samples amended with E-330 moderately resisted wetting.

The complete colors notations of the earthen mortars are listed in Appendix D. The following table summarizes the changes:

AMENDED MORTAR COLOR CHANGE
(Compared to dry and moist loose, unamended, soil)

Amended Mortar	Dry Color	Moist Color
Aztec Ruins Blend	Slightly darker, less gray	No change or slightly lighter
Chaco Canyon BLM Quarry	Slightly lighter	Slightly darker, more gray
Mesa Verde Blend	No change or slightly darker, less gray	No change or slightly lighter, more gray
New Mexico Alcalde Adobe	Slightly darker	Slightly darker or slightly lighter

Table 14

Scanning Electron Microscopy – The following mortar samples were observed at magnifications ranging from 100x to 15,000x. *Appendix A* contains photomicrographs recorded during the observations.

1. Laboratory mortar sample made with Mesa Verde Blend soil and no Rhoplex
2. Laboratory mortar sample made with Mesa Verde Blend soil and 33% Rhoplex in water
3. Artificially weathered laboratory mortar sample, 6% E-330 Mesa Verde Blend, subjected to 15 cycles of wetting/drying
4. Field sample of E-330-amended Coyote Village (Mesa Verde) mortar in good condition
5. Field sample of E-330-amended Far View Ruin (Mesa Verde) mortar in good condition
6. Field sample of E-330-amended Far View Ruin mortar in deteriorated condition
7. Field sample of E-330-amended Long House mortar (Mesa Verde) in deteriorated condition

8. Field sample of E-330-amended South Gap soil from test wall at Chaco Canyon (from 1976 Fenn test)
9. Field sample of bitumen-amended mortar from Aztec Ruins
10. Field sample of adobe from the roof of the University Museum, Philadelphia (from 1975 Butterbaugh test)

The primary beam power was set at 3KV for all of the SEM investigations. Transparent, amorphous and with extremely fine emulsion particle size, Rhoplex E-330 is not easy to find in soils; its presence is subtle. Efforts to find the material using optical microscopy proved futile, but it did reveal itself at magnifications of approximately 5,000x in the scanning electron microscope. Much of the SEM investigation focused on Mesa Verde soils, both mortar samples returned to the lab from the park, and test mortar samples made of Mesa Verde Blend. These soils were chosen because of their characteristic failures, and because representative samples of both sound and deteriorated mortar were collected in the field.

Also investigated was a sample of Dennis Fenn's E-330-amended earthen mortar from the test walls constructed at Chaco Canyon in 1976, and Darrel Butterbaugh's 1975 amended adobe from the roof of the University Museum in Philadelphia. Finally, a sample of bitumen-amended mortar from Aztec Ruins was scanned to provide a comparative view of another polymer amendment.

First scanned were two laboratory samples of Mesa Verde Blend, one amended with 33% E-330, and one unamended. At 5,000x magnification, two differences between the mortar samples were revealed. The first was strands of polymer bridging microcracks in the amended soil, probably formed as the soil contracted while drying, pulling the coalescing emulsion concentrated in the mortar voids across the opening. The second was a smooth, thin coating of polymer found in the valleys formed by sand particles of the amended mortar. Neither feature could be found in the unamended mortar.

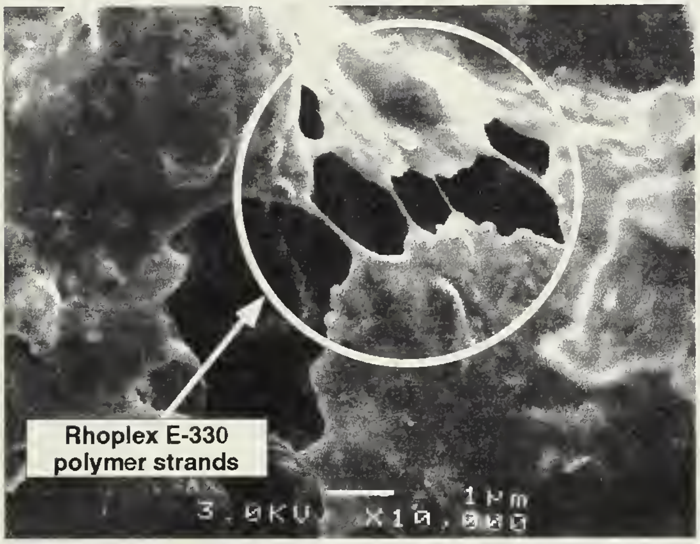

Figure 19. A mortar sample taken from Far View Ruin, a mesa-top site at Mesa Verde National Park, reveals the characteristic polymer strands bridging a microcrack in the soil. The polymer is an adhesive, and joins the particles of soil at the microscopic level. This SEM scan is 10,000 power. The white bar represents 1 µm.

The characteristic polymer strands were easily found in Fenn's test mortar, even after 20 years of exposure to Chaco Canyon weather. The strands were not easy to find in Butterbaugh's adobe sample, probably because the soil is very sandy, much coarser than Fenn's South Gap soil, and probably shrank little while drying, forming few microcracks.

Another characteristic feature of E-330-amended soil, particularly in samples deteriorated by natural weathering or laboratory stresses, such as wetting and drying, was the appearance of broken polymer film, feathery remnants of the coating that once held the mortar together. These were found in sound, undeteriorated mortar, but not as frequently as in deteriorated mortar samples. And the SEM examination was always of a broken edge, so the appearance of broken polymer is not unexpected. But in soils that were subjected to dimensional change because of wetting and drying, or freezing and thawing, the feathery fragments were much more common.

The appearance of the broken polymer film in the deteriorated mortar supports the suspicion that the acrylic cannot prevent water from reaching the active minerals, and is simply not strong enough to resist the resulting dimensional changes caused when the clay minerals absorb water and expand, or when saturated soils expand while freezing. High clay content soils eventually break the polymer bonds, rendering the mortar more susceptible to water damage. In soils with predominately

sand-sized particles, the lack of swelling and shrinking in the presence of water allows the polymer fabric to stay intact, cementing the soil particles together even in damp conditions. Sandy soils also are better drained, not as susceptible to freezing as soils with significant amounts of clay.

The bitumen-modified soil has an entirely different appearance when viewed with the scanning electron microscope. The hydrophobic asphalt coating is quite thick, compared to the E-330, preventing water from contacting the soil minerals, and at the same time binding the soil particles together.

6

DISCUSSION AND CONCLUSIONS

The analysis, testing and characterization of the Southwestern soils and of the earthen mortars revealed much about the interaction of earthen materials and Rhoplex E-330. In this summary, the test data will be assessed, and the information considered within the context of site parameters and material usage.

6.1 Soil Characterization

For this study, most of the recognized standard tests and characterizations necessary for a basic understanding of the soils were performed on the 17 soils under study. The table below lists the major characteristics of the four soils and soil blends used for the second part of the study, the tests of amended and unamended earthen mortars.

SOIL CHARACTERISTICS SUMMARY

Soil: Characteristic:	Aztec Ruins Blend	Chaco Canyon BLM Quarry	Mesa Verde Blend	New Mexico Alcalde Adobe
Grain Size Distribution (%): Coarse Sand-Fine Sand-Silt-Clay	65-14-6-15	40-25-11-24	35-35-14-16	81-3-9-7
Carbonate Content	2.4%	3.8%	8.1%	3.9%
pH (water/$CaCl_2$)	7.6-7.7 / 7.3	8.2 / 7.8	7.7 / 7.5	7.6-7.7 / 7.3
Color	10YR 5.5/3 pale brown/brown	10YR 4.5/3 brown/dark brown	7.5YR 5/4 brown	10YR 6/3 pale brown
Plastic Limit	16.7	indeterminate	19.2	indeterminate
Liquid Limit	23.8	19.5	21.9	indeterminate
Plasticity Index	7.1	indeterminate	2.7	indeterminate
Linear Shrinkage	3.5%	4.9%	4.6%	0.4%
Volumetric Shrinkage	9.2%	15.4%	11.3%	3.3%

Table 15

Soils are very complex building materials. Differences in mineralogy, particle size and distribution, chemical content, organic content, grain shape, and other variables can greatly affect the performance of soils as elements of architecture.

There is abundant literature describing earthen construction, and techniques and technology, but little specific information about earthen mortars, probably because they are considered a minor component of masonry construction. But much of the adobe literature applies directly to the problems and issues of earthen mortars; the materials are the same, and the processes of decay are identical, only the scale is different. Many of the positive characteristics of adobe soils are positive characteristics of earthen mortars, for example low shrinkage and subsequent minor cracking, durability in the face of abrasion and moisture, and adequate strength. Virtually all of the soil texts are in agreement that the wide variability in soil components makes it difficult to prescribe specific formulas for adobes. That does not mean that recipes for successful adobe soils are unusual, or that the recipes are not useful.

Houben and Guillaud write:

> The limits of the zones recommended [for adobe] are approximate. The tolerances permitted vary considerably. Present knowledge does not justify the application of narrow limits. It is admitted that many soils which fail, for one reason or another, to comply with the requirements have been found satisfactory in practice; all that is claimed for the recommendation is that materials which comply with it are more likely to be satisfactory than those which do not. The zones are intended to provide guidance and are not intended to be applied as a rigid specification.[91]

Clifton discusses various adobe specifications that call for 70-80% sand, 9-28% clay, 20-30% silt and clay, and equal amounts of silt and clay.[92] McHenry presents an "average" recipe based on the analysis of many successful adobe buildings: 23% coarse sand, 30% sand, 32% silt, and 15% clay.[93] Fenn recommended a soil consisting of approximately 70% sand, 20% clay, and

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91 Houben and Guillaud, *Earth Construction*, 114-115.

92 James R. Clifton, *Preservation of Historic Adobe Structures – A Status Report* (Washington: National Bureau of Standards, 1977), 4.

93 Paul Graham McHenry, Jr., *Adobe and Rammed Earth Buildings* (Tucson: University of Arizona Press, 1984), 51.

less than 10% silt.[94] Houben and Guillaud recommend a range broad enough to incorporate 50-80% sand, 18-30% silt and 10-30% clay.[95] As for adobe, the first requirement for a good soil mortar is good soil.

The particle size distribution test provided the most important information about the unamended soils that could help explain their behavior. The proportion of particle sizes, particularly silts and clays, seems to be directly related to their performance as amended mortars. Two soils, Aztec Ruins Blend and New Mexico Alcalde Adobe, were much lower in total silt and clay (21% and 16% respectively) than Mesa Verde Blend or Chaco Canyon BLM Quarry (30% and 35% respectively). The two soils with less silt and clay, and more sand, performed better when amended with E-330 in freezing and thawing and wetting and drying than did the other two soils.

The shrinkage tests also gave important clues to the performance of these soils in the field. The two soils highest in shrinkage, Mesa Verde Blend and Chaco Canyon BLM Quarry, performed the poorest in laboratory experiments. New Mexico Alcalde Adobe shrank almost not at all and, amended with 33% E-330, faired best in the strenuous tests of wetting/drying and freezing/thawing. The Aztec Ruins Blend cracks in the field, when used as capping, but still its volumetric shrinkage was relatively low (9.2%). Its relatively high sand content gives it acceptable performance when modified with E-330.

The affect of the acid-soluble, carbonate, content of the mortar soils on the durability of the mortar is unclear. Generally, the carbonate content of the soils was inversely related to their performance; the higher the carbonate content, the worse the performance. The exception to this was the New Mexico Alcalde Adobe soil which had the second highest carbonate content (3.9% to Mesa Verde Blend's much higher 8.1%). But the adobe soil also had much more sand (84%) than any of

94 Fenn and Deck, "Third Annual Report", 2.
95 Houben and Guillaud, *Earth Construction*, 114.

the other soils. The question of whether carbonate content in the range of 0-10% affects mortar behavior, either amended or unamended, would have to be resolved by more direct experimentation.

6.2 Consistent Effects of E-330

Rhoplex E-330 had some predictable effects on all the soils tested. Measured by resistance to bending, an increase in the proportion of E-330 to water in the mortar mix always resulted in an increase in strength, regardless of soil type. Measured by the transmission of water vapor, an increase in the amount of E-330 in the earthen mortar always decreased the permeability of the mortar. Compared with unmodified soil, the addition of even 6% E-330 (the lowest percentage tested) resulted in increased resistance to water, for none of the unmodified earthen mortar cylinders survived the initial five hours of water immersion in the wetting and drying test, and all of the 6% cylinders did. The addition of E-330 always helped the soil cylinders resist slumping as they wicked water from an absorbent pad in the freezing and thawing test, and the more E-330 in the mortar, the better the resistance. As expected, the addition of E-330 had only a minimal effect on the color of the earthen mortar, when compared to unmodified soil.

6.3 Amended and Unamended Earthen Mortar Characteristics

The four soils tested as components of earthen mortars were quite varied in their properties. As measured by resistance to bending, the two soils containing most sand, Aztec Ruins Blend and New Mexico Alcalde Adobe, had the least strength, either modified or unmodified. The soils higher in clay and silt, Mesa Verde Blend and particularly Chaco Canyon BLM Quarry, were significantly stronger. The Chaco soil was almost twice as strong as the Alcalde adobe, the weakest soil.

The relationship between soil activity, as measured by linear and volumetric shrinkage, and clay and silt content is direct. The soil with the largest fine fraction, Chaco Canyon BLM Quarry, exhibited the largest amount of shrinkage. The soil with the least, New Mexico Alcalde Adobe, exhibited very little shrinkage. Mesa Verde Blend and was next highest in shrinkage and Aztec Ruins Blend third. (The shrinkage characteristics of amended soils were not tested, but other research with an acrylic amendment in soil indicated that small amounts, 2% by weight, have little effect on linear shrinkage.[96])

No such clear relationship was evident in terms of water vapor transmission. The sandiest soils, the Alcalde adobe and Aztec Ruins Blend, were the most and least permeable, respectively. The finer textured soils were in-between, with the Mesa Verde soil more permeable than the Chaco Canyon soil, the soil highest in clay and silt (35% total) of the four tested. As the E-330 proportion was increased, the total permeability of all samples was diminished, but the relationship between the soils remained the same. Particularly efficient grain packing might explain the Aztec Ruins soil's relatively low permeability.

In the wetting and drying test, the unmodified soils all failed in the first five-hour immersion, but incidental observation revealed that the two sandier soils failed almost immediately, within a few minutes. The soils higher in clay and fine particles lasted longer, but still disintegrated in five hours.

In the freezing/thawing test, the soils exhibited a marked difference. The two sandiest soils slumped, loosing grain to grain adhesion. They maintained roughly the same volume as originally cast, though they were shorter and wider. The soils higher in clays swelled, increasing in volume, expanding in width while roughly maintaining the same height. The soil highest in clay- and silt-

[96] C. Atzeni, L. Massidda and U. Sanna, "Technological Properties of Earth-Based Construction Materials Treated with Hydraulic Cement or Acrylic Polymers" In *7th International Conference on the Study and Conservation of Earthen Architecture*, Silves, Portugal, 24-29 October, 1993, 566-7 (Lisbon: DGEMN, 1993).

sized particles, Chaco Canyon BLM Quarry, also had the greatest expansion. (This soil also exhibits the greatest shrinkage.) With increasing levels of E-330, the cylinders of all soils tended to deform less, although the sandier soils were more constrained, remaining closer to their original (dry) dimensions.

6.4 Earthen Mortar Durability and Deterioration

Mortar repair is not an exact science, and there are perhaps more variables in the design and application of earthen mortars than there are constants. Mortar performance in the field can be affected by a combination of variables not easily duplicated in the lab. The variables include the following:

- The weather on the Colorado Plateau is inconstant. Air temperatures can vary dramatically over a 24-hour period, and the temperature difference of materials in the shade and in direct sunlight can be great. Water is delivered year-round in the form of rain, snow, condensation and frost; and the normally dry air promotes rapid evaporation. Thunderstorms are not uncommon.
- The soils used for repairs are not identical to the original material, and in fact the repair materials used are not absolutely constant, but vary from one soil source to another, and potentially could vary by particle size distribution within soils from the same source.
- Masonry conditions vary widely; some stones are laid with Portland cement bedding mortar, some with amended or unamended earthen mortar. Some sites are fully exposed to weather, some are sheltered in sandstone alcoves. Some masonry walls stand alone, some are backed by rubble or soil fill, which can become saturated with water, and some walls enclose roofed, interior, spaces. Some walls are above grade, some below.

- Techniques for mortar repair vary with personnel, and proportions of Rhoplex E-330 and water can vary from day to day, since the material amounts are not measured exactly. And while records are kept of the maintenance performed, it is not always possible to tell exactly what conditions were present when a particular mortar joint was pointed, or when a wall was capped, or what weather conditions prevailed as the mortar repair dried.

The effectiveness of any soil amendment, including Rhoplex E-330, depends in part on all of the variables above. Each of these variables is discussed below.

6.4.1 Climate

It takes two ingredients to make earthen mortar, earth and water. It requires only water to destroy it. Since most of the ruins stand exposed to weather, their custodians face a relentless opponent. Water, and its interaction with other environmental agents, is the major factor in earth construction deterioration. Water attacks the earthen mortars during rainstorms, and snow sets on wall tops resulting in water running slowly down masonry walls and soaking into mortar and earthen fill.

Figure 20. The climate of the Colorado Plateau, with year-round rain and snow, and broad temperature fluctuations, places great stress on the earthen components of remaining Anasazi architecture. The challenge of maintaining the ruins while using visually and physically sympathetic materials is great.

Clear nights on the Colorado Plateau in the spring and fall can cause the temperature to plummet below freezing. Winter also brings freezing temperatures, but the sun can warm ruin walls above the melting point.

Water movement, wetting and drying, and freezing and thawing of damp masonry are proven agents of masonry damage, and the major agent of deterioration at these Anasazi ruins.

In hot climates, the temperature of a wall surface can rise 72°F in half an hour, when the sunlight reaches a previously shaded wall. In combination with water, the heating may produced cracks and crusts by promoting rapid evaporation.[97] Sharp changes in both temperature (±45°F) and humidity (±75% r.h.) were reported in an adobe wall in Iraq when struck by the direct afternoon sun, and again at sunset.[98]

The effect of thermal stress on earthen mortars is unknown. Heat has been demonstrated to change the properties of adobe, increasing both water resistance and compressive strength. However, the experiments were conducted with unamended adobes, at temperatures between 20-200°F.[99] Certainly Southwestern ruins walls in the direct summer sun could exceed a surface temperature of 100°F, but temperatures in the interior of the walls would be cooler, the actual temperature gradient depending on wall material, thickness, orientation and backing material, if any. Any change in properties due to heat would probably be limited to a layer near the surface.

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97 Giacomo Chiari, "Characterization of Adobe as Building Material: Preservation Techniques" in *Adobe: International Symposium and Training Workshop on the Conservation of Adobe*, Lima-Cusco, Peru, Sept. 10-22, 1983, 36 (Rome: UNDP/UNESCO/ICCROM, 1983).

98 Giorgio Torraca, Giacomo Chiari and Giorgio Gullini, "Report on Mud Brick Preservation" *Mesopotamia* 7 (1972): 268.

99 Erhard M. Winkler, "Influence of Sun Heat on Clays" *Soil Science* 82 (1956): 195.

6.4.2 Soils

The tests performed on the 17 Southwestern soils only reveal the characteristics of the small samples gathered by the researcher or allies in the field. Some variability in soil characteristics should be expected within each new batch of soil collected for ruin repair. In the case of the Mesa Verde Blend soil, the proportions were selected to represent a typical Mesa Verde mortar; the tested mix certainly does not represent all the mortar varieties at that site.

Of all the characteristics of the soils, particle size distribution and mineralogy are probably the greatest factors in the durability of earthen mortars. Soils containing predominately sand shrink almost not at all, but are not durable when exposed to water. Clay soils are more water resistant, but are prone to swelling and shrinking, causing cracks that invite water entry, and ultimately, damage.

Earthen mortars at ruin sites are asked to perform in difficult circumstances. Adobe bricks of the same material might perform well. Small cracks or slight erosion that might be inconsequential on an adobe block can be significant in a earthen mortar joint. It is not easy to fine tune an earthen mortar for maximum durability, and the differences between poor, better and best may be very small. This may be compounded by, or caused by, the lack of soil choice at some National Park Service sites.

6.4.3 Masonry

At Mesa Verde, original earthen plaster and mortar with original finger marks still remain 800 years after the masons disappeared. But these sites are sheltered in massive sandstone alcoves. Here, any needed repairs can be made with unamended soils and durability is assured. Most ruins sites are exposed to the weather, but architectural differences – directional orientation or structural

relationship of one room to another – result in some walls suffering greater mortar damage than others.

The geometry of some walls causes snow to accumulate and the path of the melting water can be traced in the eroded mortar. Other walls, such as shaded, subterranean kiva walls, may wick water from saturated fill, never properly drying.

Walls reconstructed with Portland cement bedding mortar during stabilization may have a very shallow surface joint, providing little area for the earthen mortar to adhere, and little mass to help absorb the effects of weather or movement. Mortar in such joints often cracks, and sometimes falls out.

6.4.4 Technique

The use of amendments in the field is not a science. The crews responsible for maintaining the ruins do not work in a laboratory. Their tools are shovels, buckets and trowels. They need guidelines, techniques and materials that are practical and efficient.

Proportions of E-330 or other polymer amendments to soil almost certainly vary from batch to batch, and weather conditions may not always be ideal. Records are kept describing which walls are repaired on any given day, but they are not so complete as to include exact weather conditions, or overnight weather conditions.

6.4.5 Acrylic Amendments

Amendments alter the properties of earthen mortars in some subtle and unsubtle ways. Although the addition of E-330 always makes earthen mortars stronger, it also reduces permeability. This does not seem to be a problem with very sandy soils which contain little natural material to

bind them together. The polymer serves that function, and the large grains of the soil maintain enough porosity and permeability to resist damage from freezing. The relative lack of activity, swelling and shrinking, allow the polymer to function undamaged.

Fine grained soils may not have the porosity and permeability to spare, and water trapped in the soil pores can freeze, damaging the clay and polymer bonds holding the mortar together. The fine polymer net formed when the amended mortar dries cannot prevent the powerful attraction of clays for water. The resulting expansion and contraction of the clay minerals as the soil cycles between wet and dry and frozen and thawed, ruptures the polymer bond.

It would be possible to make an acrylic-modified mortar that could withstand the forces of freezing, and the expansive forces of soil clays, and possess durability measured in years. But it would require so much polymer that instead of polymer-amended soil, the final product would more fairly be called soil-modified polymer. And the resulting mortar's properties of permeability and hardness would make it as incompatible as Portland cement, and very expensive.

It was originally suspected that test mortar specimens dried below the T_g of E-330 might perform differently, more poorly, than samples dried above the T_g. This was not the case. There is an effect called hydroplasticization which effectively lowers the minimum film formation temperature, MFT, below the nominal T_g. Hydroplasticization is the softening (plasticizing) of the polymer with water. It depends somewhat on the pH of the system and drying time. Some polymers show very little plasticization, while all acrylics show the effect to some degree. It is possible that hydroplasticization was responsible for lowering the MFT enough to allow film formation in the cold-dried mortar specimens. Polymer scientists are still researching the precise mechanism of coalescence and loss of individual particle identity (film formation).[100]

[100] Donald Glusker, correspondence with author, 31 January 1996, Philadelphia.

Even though no ill effect of drying below the glass transition temperature was observed in the laboratory tests of earthen mortars, the few samples frozen and then dried at ambient laboratory temperatures did not fair as well; they were much weaker in bending, and they developed fine cracks in the wetting/drying test. It is not hard to imagine conditions in the field, conditions of wind and low humidity, when flash cooling of earthen mortars might lower the mortar temperature well below the T_g. And if the temperature dropped at night, earthen mortars could dry quickly in the cold dry air, perhaps impacting film formation. Likewise in the summer, mortars in the direct sun might dry too quickly, potentially damaging film formation.[101] These speculations of thermal effects could be investigated in the lab, or in careful field trials.

Clifton reported the coefficient of thermal expansion for adobe soils in the rather large range of 9×10^{-7} to 1.4×10^{-5} in/in/°F.[102] Eyre narrowed it to approximately 2-3 x 10^{-6} in/in/°F.[103] The coefficient of thermal expansion for polymethyl methacrylate is approximately 2.8-5 x 10^{-5} in/in/°F.[104] This overlap in thermal response probably means that heating (and cooling) of the soil at temperatures above the T_g of the polymer place no important stress on the Rhoplex-soil bond, because the polymer is somewhat elastic.

But another thermal effect related to the T_g might be at work in the field. Once the E-330 polymer film has formed, it becomes brittle below 50°F. This can be demonstrated by drying a patch of Rhoplex on foil or plastic wrap, and placing it in the freezing compartment of a refrigerator for a few minutes. When removed, the formerly flexible film snaps and shatters when bent sharply. The polymer in acrylic-modified earthen mortars should become more brittle below 50°F. This would not be important unless cold mortar changed dimensions, for example when mortar near the freezing point becomes wet and begins to swell, or damp mortar freezes and swells, or cold mortar is

101 Interview with Robert Falconio.
102 Clifton, *Preservation*, 6.
103 Eyre, "The Physical Properties of Adobe", 23.
104 Irvin I. Rubin, ed., *Handbook of Plastic Materials and Technology* (New York: John Wiley & Sons, 1990), 365.

suddenly warmed by direct sunlight. Repeated cycles cold wetting and occasional freezing could seriously strain, or break, the polymer bonds within the mortar.

7
RECOMMENDATIONS

> The fact that no "final solution" is or will be available for the adobe conservation problem is never stressed enough. This is true for all materials, but particularly so for adobe, whose weak characteristics have always been counteracted with regular maintenance and extensive rebuilding. The fact that modern conservators obviously cannot act with the same freedom in rebuilding damaged parts of historic buildings, simply means that, on the long range, they are condemned. All we can hope for is to enhance their life expectancy.[105]

Ideally, the earthen mortars at the Anasazi sites on the Colorado Plateau, and at other sites in the Southwest, would not need amendments. But standing vacant and exposed to weather without roofs or plasters, often without adjacent supporting walls, the ruins need assistance, and the National Park Service continues to look for solutions that preserve the overall appearance as found, but also reduces the maintenance cycle. Maintaining pointing and capping in good repair is sound practice, it keeps water out of wall cavities and interior spaces where it can cause major damage.

Polymer emulsion amendments are not *the* answer to earthen mortar durability. They are a recent and current answer, the technology of the day, an attempt to improve over the cement and asphalt emulsion amendments used in prior decades. Still no perfect amendment has been found, though not for want of trying. Experimenters are subjecting adobe to ever more complex polymer amendments and consolidants. But all these chemical interventions have liabilities. Depending on the soil and the location and condition of the ruin, the real possibility must be considered that no soil amendment will lend long-term durability, without long-term problems. The positive and negative aspects of amendments other than Rhoplex E-330 must be restricted to other research; however, it is hoped that the methodology presented here will provide a baseline for future studies.

Amending soils for use as mortars is only part of the repertoire of stabilization techniques available to the custodians of the sites. The repertoire also includes backfilling and sheltering, sacrificial plasters and unamended soil repairs.

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105 Chiari, "Characterization of Adobe as Building Material", 37.

The first consideration for choice of repair soil should be to find the best soil, or group of soils, which meet the requirements of color and texture, established by the custodians at the sites. Current practice, based on a long history of mortar repairs at Mesa Verde and other sites, at least since James A. Lancaster's stabilization work at Mesa Verde beginning in 1935, stresses the importance of visual compatibility with the prehistoric mortars. Given this significant requirement, Rhoplex E-330 provides a suitable alternative to other amendments because it imparts no color or texture change to the soil mortar.

If a sandy soil is available (at least 60-65% coarse sand, with 10-15% clay), or can be made with the addition of sand, the soil should perform well when amended with Rhoplex E-330. And all other factors being roughly equal, the soil with the lowest shrinkage should be chosen. If strength in bending is not a consideration, the durability of sandy soils modified with this acrylic emulsion is measurably better than soils containing more silt and clay.

The soils impart the major properties to an acrylic-modified earthen mortar, not the other way around. An acrylic emulsion used in proportions of up to 33% in water, cannot overwhelm the natural characteristics of a soil. Porous and permeable sandy soils remain porous and permeable. Active fine-grained soils continue to shrink and swell. This is a critical and important factor in understanding the relationship among soil types, Rhoplex E-330 and their performance.

There is not one answer to solving the problems of earthen mortar deterioration; there are only alternative solutions, each with benefits and liabilities.

7.1 Specific Recommendations

The only way to improve the performance of E-330-modified earthen mortars at Mesa Verde is to change the particle size distribution of the soil used as mortar. Lowering the E-330 content of the loess soil mix might lengthen the durability of the mortar in the face of freezing and thawing, but

probably would not improve its response to wetting and drying, a major problem at exposed sites. E-330 supply costs would be reduced. Adding sand to the mix until approximately 60-65% of the soil blend was larger than 0.075 mm (coarse sand) should dramatically improve the performance of the amended earthen mortar. There would be a cost involved with acquiring suitable low-carbonate sands, and the texture of a sandier soil mix would have to be judged for compatibility with existing repair mortars, and historic mortars.

The soil mix at Aztec Ruins proved to be the most durable soil tested because it contains more sand and less silt and clay than the soils used at the other two sites. The proportion of E-330 could probably be reduced to 25% (from 33%) without significantly reducing its durability, and costs would be reduced. But the soil is sandy enough that it shows no ill effects from the relatively high polymer content. The addition of more fine sand would help reduce shrinkage cracks, a problem when the soil blend is used as capping.

The Chaco Canyon BLM Quarry soil shares some characteristics of the Mesa Verde soil. It is fine-grained, and Rhoplex E-330 cannot overcome the tendency of this soil to swell and shrink, shortening its durability as mortar. Also, the stickiness of the clay when wetted, and the stickiness of the E-330 at 33%, combine to create a messy mortar hard to work with in the lab. Masonry foreman Cecil Werito at Chaco Canyon indicated that was true in the field as well, one of the reasons he switched to another amendment. However, the high activity of the BLM Quarry soil will probably stress any film-forming polymer emulsion. Two of the other Chaco Canyon soils characterized, South Gap and Tsin Kletsin, were far sandier, almost the same color, and have demonstrated superior performance with E-330. (Archaeologist Dabney Ford indicated that the Tsin Kletsin soil is not available for general use.) Perhaps the South Gap soil could be approved for use in mortar repairs, or another soil with similar grain size distribution could be located. Another option would be to add low-carbonate sand to the BLM soil until the proportion of particles larger than 0.075 mm (coarse sand) reached 60-65%.

7.2 Future Research

This study of Rhoplex-amended earthen mortar suggests some interesting questions for future research.

- It is still not clear how very cold temperatures might affect film formation in the field, and how saturated walls impact mortar drying. Using relatively inexpensive monitoring equipment, such as hygrometers, minimum/maximum thermometers, and moisture meters to probe interior of walls, some of the environmental factors which affect the durability of E-330-modified soil could be explored.
- Field trials of polymer amendments should include side by side trials of E-330 and other proven amendments, such as vinyl acetate, and perhaps an acrylic emulsion with a lower glass transition temperature. Vinyl acetate emulsion is cheaper than acrylic emulsion although it is not as stable in the presence of ultraviolet light. This might not be important in opaque earthen mortars.
- Field trials using specially modified soil mixes of varying polymer percentage also should be conducted to confirm the laboratory and existing field experimental data showing that sandy soils are the key to long-term E-330-modified earthen mortar durability.
- Mortar field trials also could be designed to address the issue of carbonate content and its effect, if any, on earthen mortar durability.
- Dennis Fenn's field sites and test walls at Chaco Canyon should be visited and assessed. The full lessons of his research begun 20 years ago have not been learned.
- Other Southwestern National Park Service sites should be surveyed to learn about soil amendment use: types of amendments used; types of soil and soil sources; uses of amended soil; and field experience with amended soils. If included with similar information about Bureau of Land Management, Forest Service and state sites in the four-corners region, a valuable database of soil stabilization practices and experience could be compiled.
- A set of laboratory and field experiments should be performed to investigate other amendments including cementitious materials such as calcium aluminate, low-salt cements (used in soil-cement combinations), and other inorganic materials such as

lime, and hydraulic lime. Although some of these materials are out of favor now (some have been badly misused in the past) each also has a record of success and durability if conditions are favorable. Perhaps there is a place in the modern inventory for some of these amendments, properly used.

- Finally, the physical tests performed on the earthen mortar samples need to be reviewed and evaluated for the relevancy of the properties measured, and modified or replaced to better represent the field conditions present on the Colorado Plateau. Specifically, the wetting/drying test and the freezing/thawing test are designed to test compressed soil-cement, a much stronger material than more fragile acrylic-modified earthen mortar. In the field the mortars are subjected to wetting, freezing and drying in unpredictable cycles, perhaps all in the same day. A modified test that alternately wets, freezes and dries a earthen mortar sample, with regular weighing, measurement and observation could more accurately reflect field conditions. Also, a mild water abrasion test might help predict the performance of earthen mortar in the field.

The more tools conservation research can place at the disposal of the custodians of these precious sites, the more flexible they can be in response to the varied but continual forces of deterioration.

Appendix A
SEM Photomicrographs

Figure 21. Mesa Verde Blend earthen mortar, 0% E-330, 1,000x magnification. In this sample of unamended Mesa Verde Blend earthen mortar, the soil particles stand out in sharp relief. Compare with the amended Mesa Verde Blend earthen mortar, *Figure 22.* White bar is 10μm.

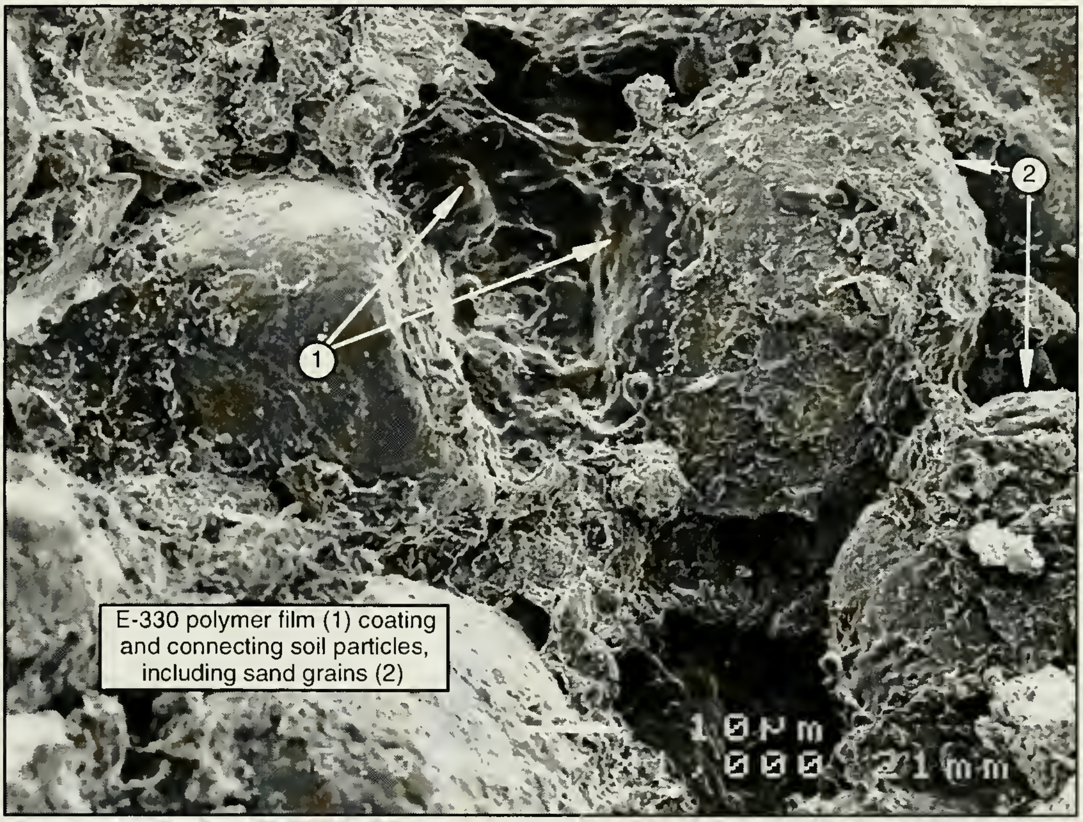


Figure 22. Mesa Verde Blend earthen mortar, 33% E-330, 1,000x magnification. The smooth Rhoplex polymer coating can be seen in a valley of the amended earthen mortar, covering the mineral fragments beneath. White bar is 10μm.

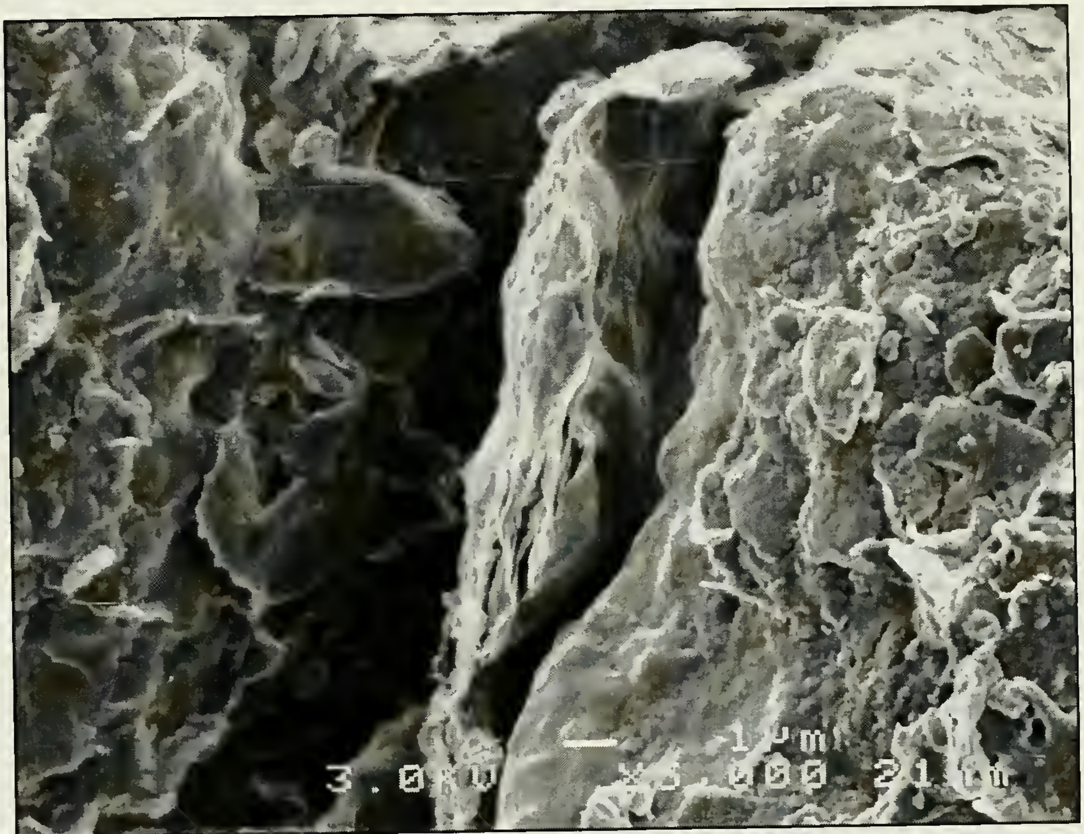


Figure 23. Mesa Verde Blend earthen mortar, 0% E-330, 5,000x magnification. The microcracks in this unamended earthen mortar sample are clean, with no debris or mineral connections between one side and the other. Compare with the amended mortar in *Figure 24*. White bar is 1 μm.

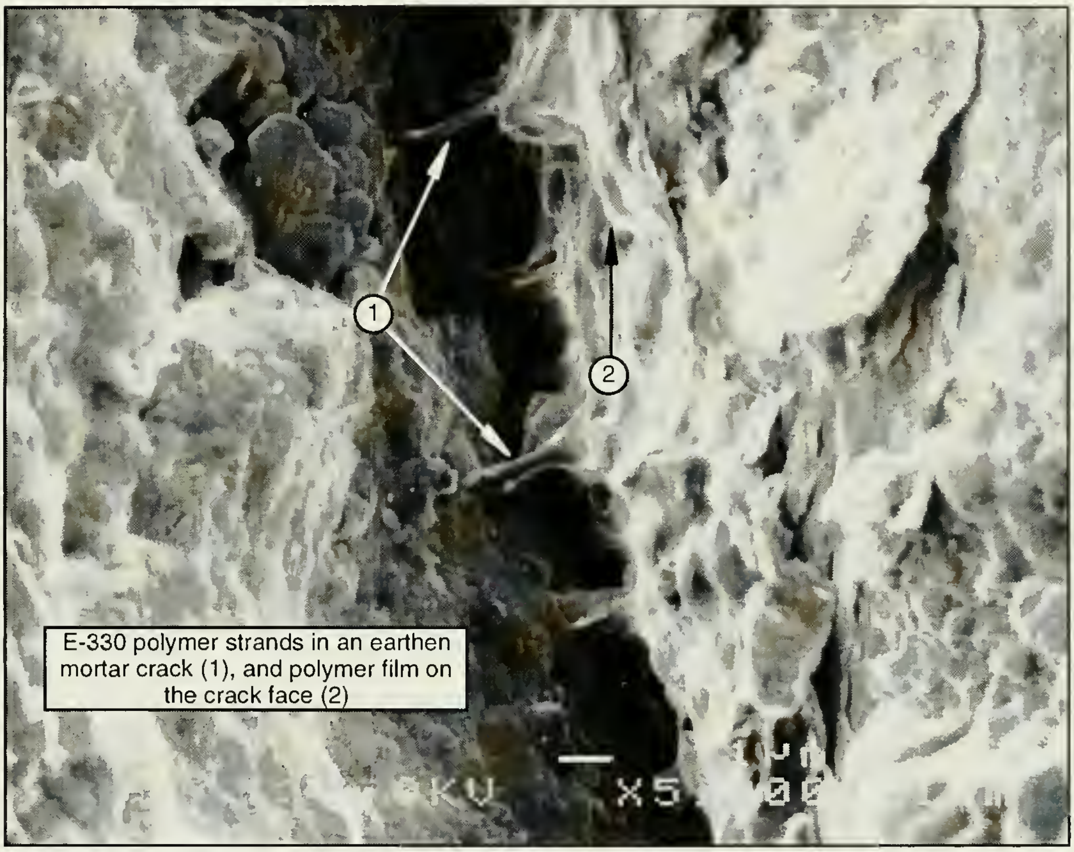


Figure 24. Mesa Verde Blend earthen mortar, 33% E-330, 5,000x magnification. The polymer strands connecting one side of an earthen mortar microcrack with the other are typical of the appearance of Rhoplex E-330 in a fine-textured soil. They probably result from soil contraction during drying, and coalescence of the polymer concentrated in the mortar voids. White bar is 1 µm.

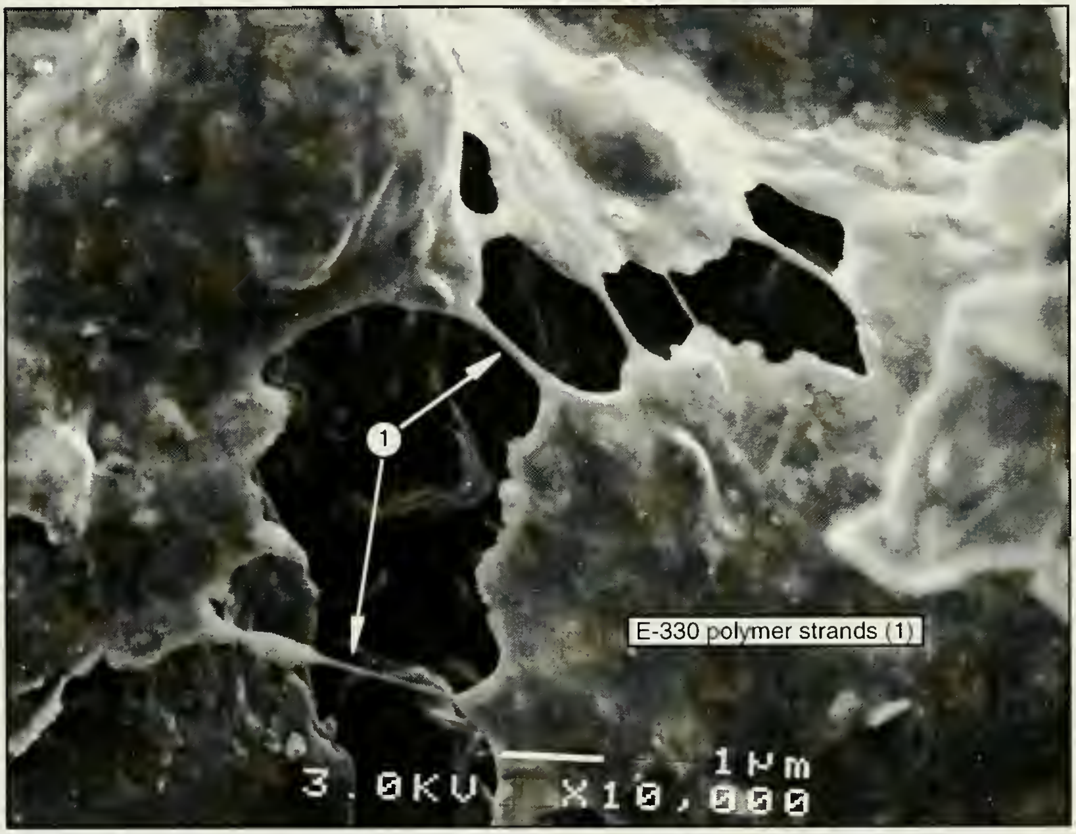


Figure 25. Far View Ruin amended earthen mortar, Mesa Verde, 10,000x magnification. This sample was taken from a dry, intact, piece of amended mortar (between 25% and 33% E-330) at Far View Ruin, on the top of Chapin Mesa. The same distinctive polymer strands seen in the laboratory samples made with Mesa Verde Blend also are visible here. Another view of the sound Far View amended earthen mortar is shown in *Figure 26*. White bar is 1 µm.

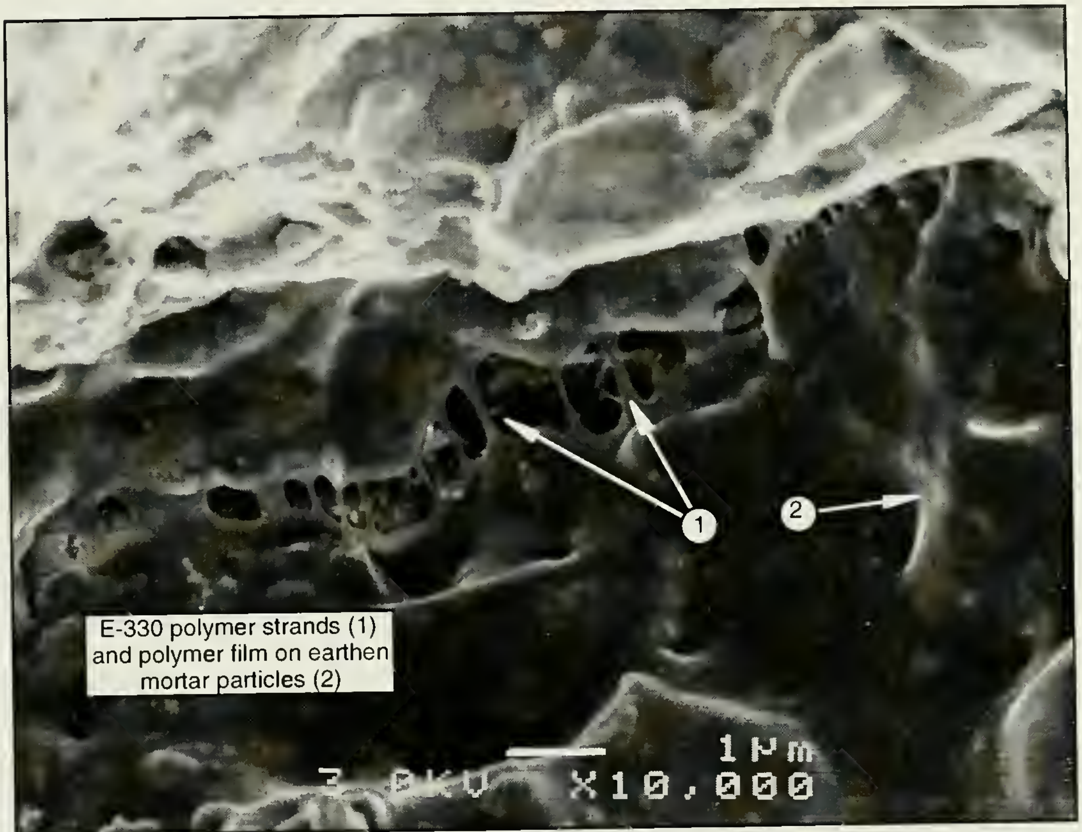


Figure 26. Far View Ruin amended earthen mortar, Mesa Verde, 10,000x magnification. The polymer strands bridging an amended earthen mortar crack and the smooth polymer coating on the earthen mortar face are visible in this sample of undeteriorated mortar. (Mortar contains between 25% and 33% E-330.) White bar is 1 µm.

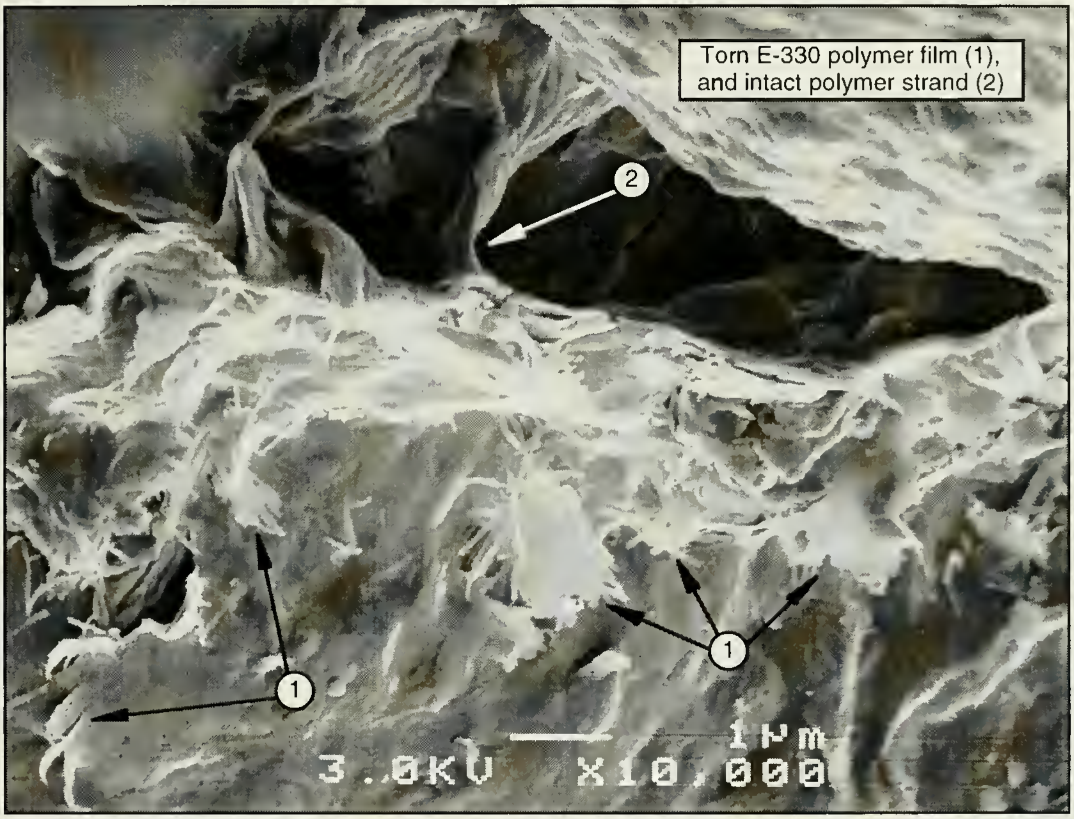


Figure 27. Far View Ruin amended earthen mortar, Mesa Verde, 10,000x magnification. This sample was taken from a highly deteriorated location. The mortar sample was in the path of water, from rain and melting snow, running down the ruin face, subjecting the mortar to frequent wetting and drying. Broken, feathery, fragments of the E-330 polymer film are visible. The polymer was unable to resist the dimensional changes caused either by wetting and drying of the soil minerals, or the expansion caused by freezing of the moisture in the soil. (Mortar contains between 25% and 33% E-330.) White bar is 1 µm.

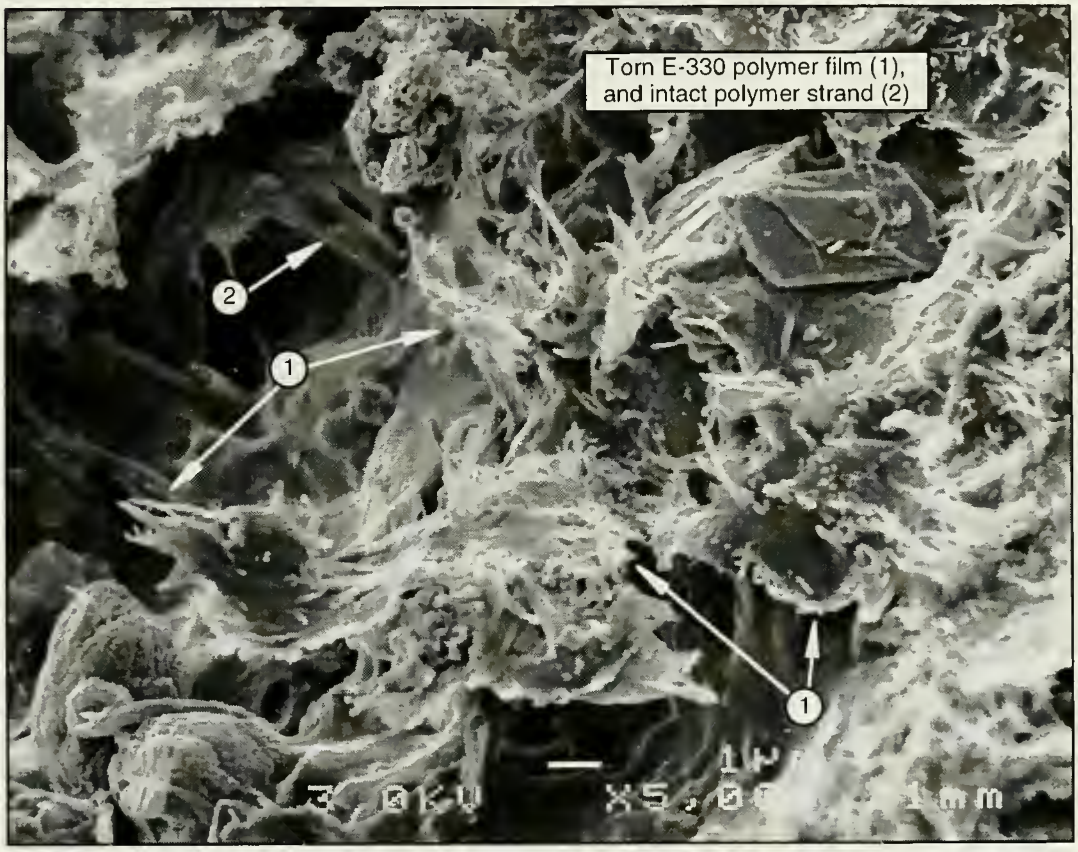


Figure 28. Mesa Verde Blend earthen mortar, 6% E-330, 5,000x magnification. Compare this photomicrograph of Mesa Verde Blend earthen mortar, subjected to wetting and drying in a laboratory test, to the Far View Ruin mortar , *Figure 27*. The same feathery, broken, polymer film is visible. This sample was a flake detached from an earthen mortar sample after 17 cycles of wetting and drying. White bar is 1 μm.

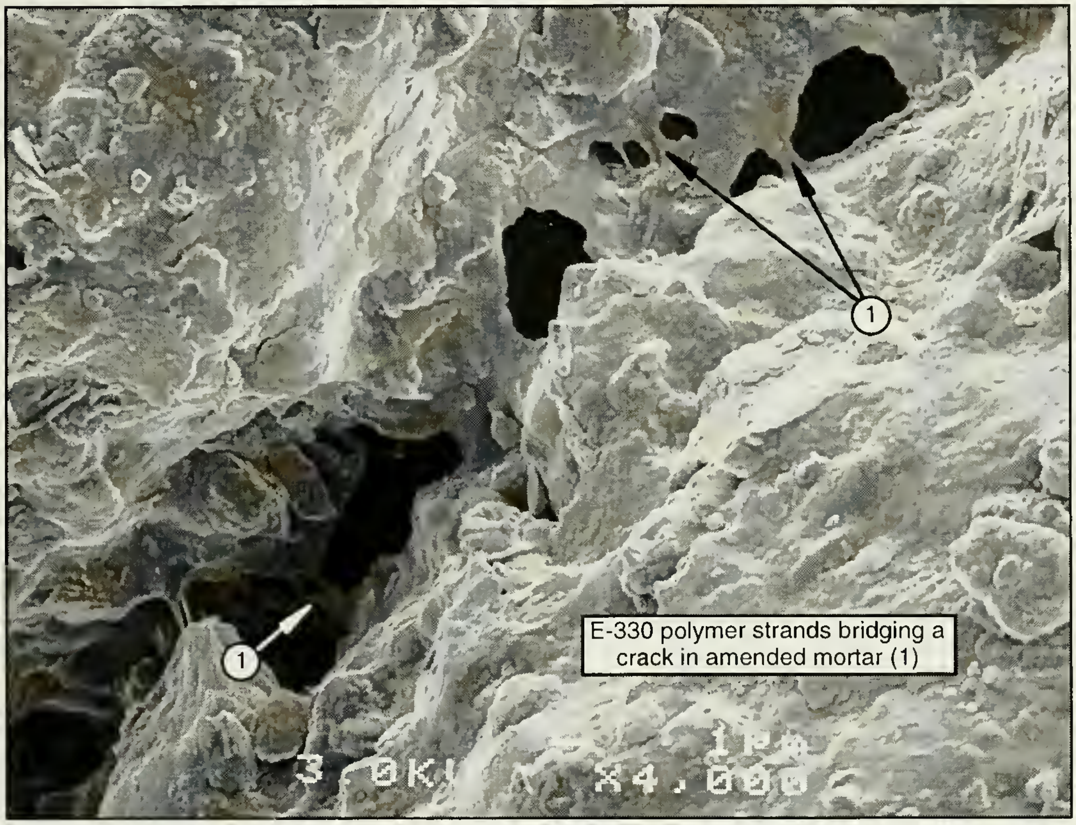


Figure 29. Chaco Canyon South Gap amended mortar, 29% E-330, 4,000x magnification. The E-330 polymer strands are revealed in this sample of mortar from Dennis Fenn's test wall near the visitor center at Chaco Canyon. The mortar was installed in 1976, and is still in sound condition. South Gap soil is a sandy soil (85% sand, 15% silt and clay). White bar is 1 μm.

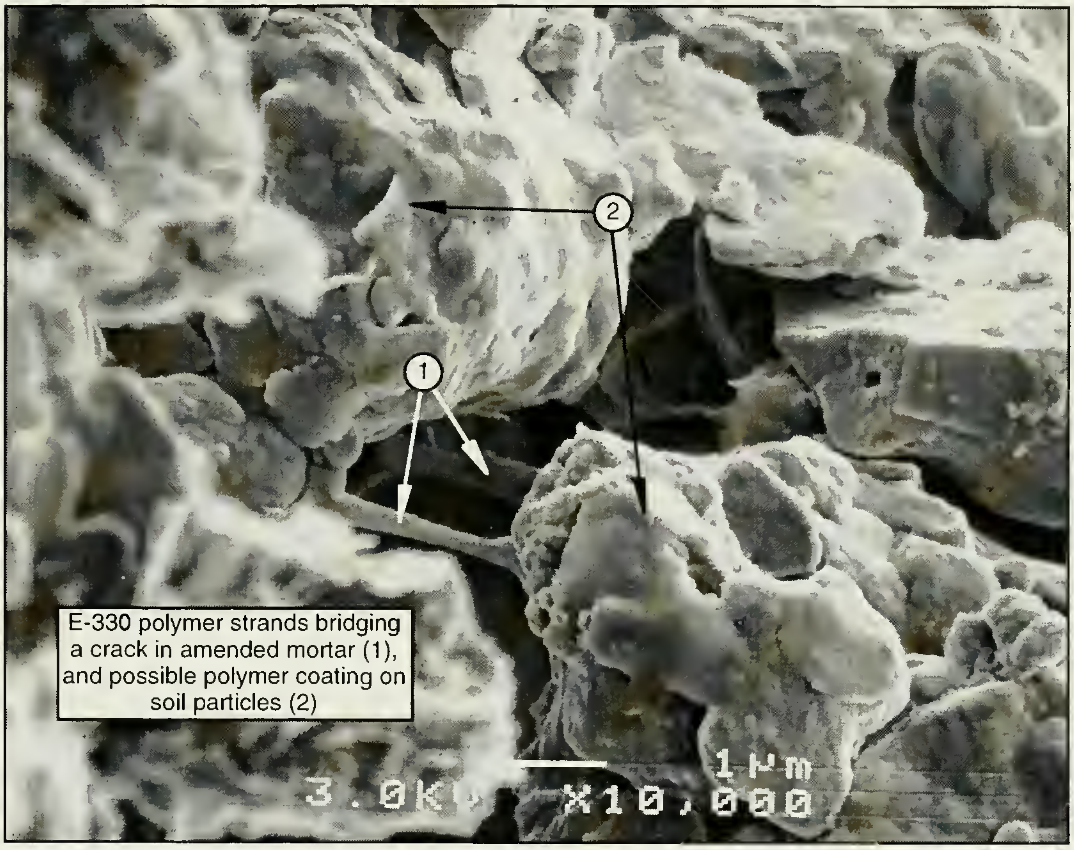


Figure 30. Chaco Canyon South Gap amended mortar, 29% E-330, 10,000x magnification. Another view, at higher magnification, of the polymer strands in the Fenn mortar, and possibly the polymer coating on the soil particles. The polymer strands are less frequent in sandy soils than in soils more rich in clay, possibly because the soil shrinks less while drying, forming fewer microcracks. White bar is 1 μm.

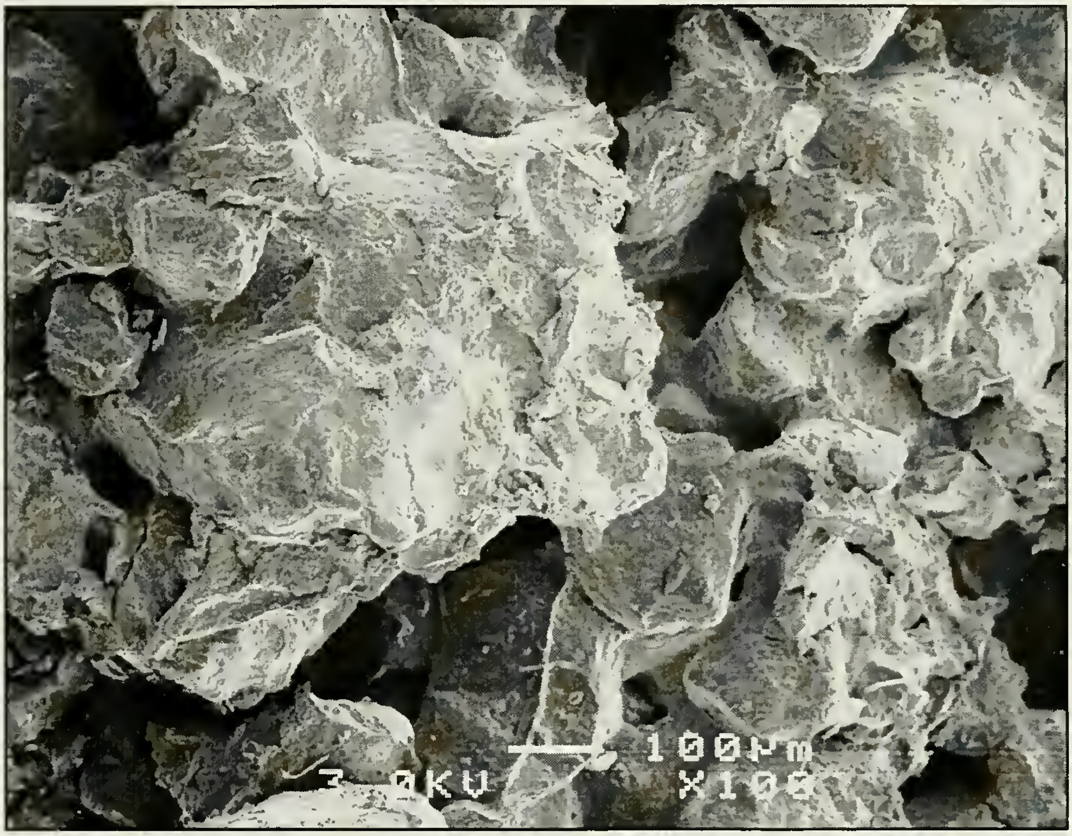


Figure 31. Butterbaugh amended adobe, 25% E-330, 100x magnification. This sample was taken from an adobe brick made by Darrell Butterbaugh in 1975 and placed on the roof of the University Museum in Philadelphia that year. Made from an obviously sandy soil, the adobe is still intact. Compare the soil texture with *Figure 32*, a Mesa Verde amended mortar. Both images are 100x magnification. White bar is 100 µm.

Figure 32. Coyote Village amended mortar, Mesa Verde, 100x magnification. This amended earthen mortar sample (between 25% and 33% E-330) was taken from a deteriorated mortar location at Coyote Village, near Far View Ruin, on Chapin Mesa. Compare the texture of this soil with the sandy modified adobe sample in *Figure 31*. White bar is 100 μm.

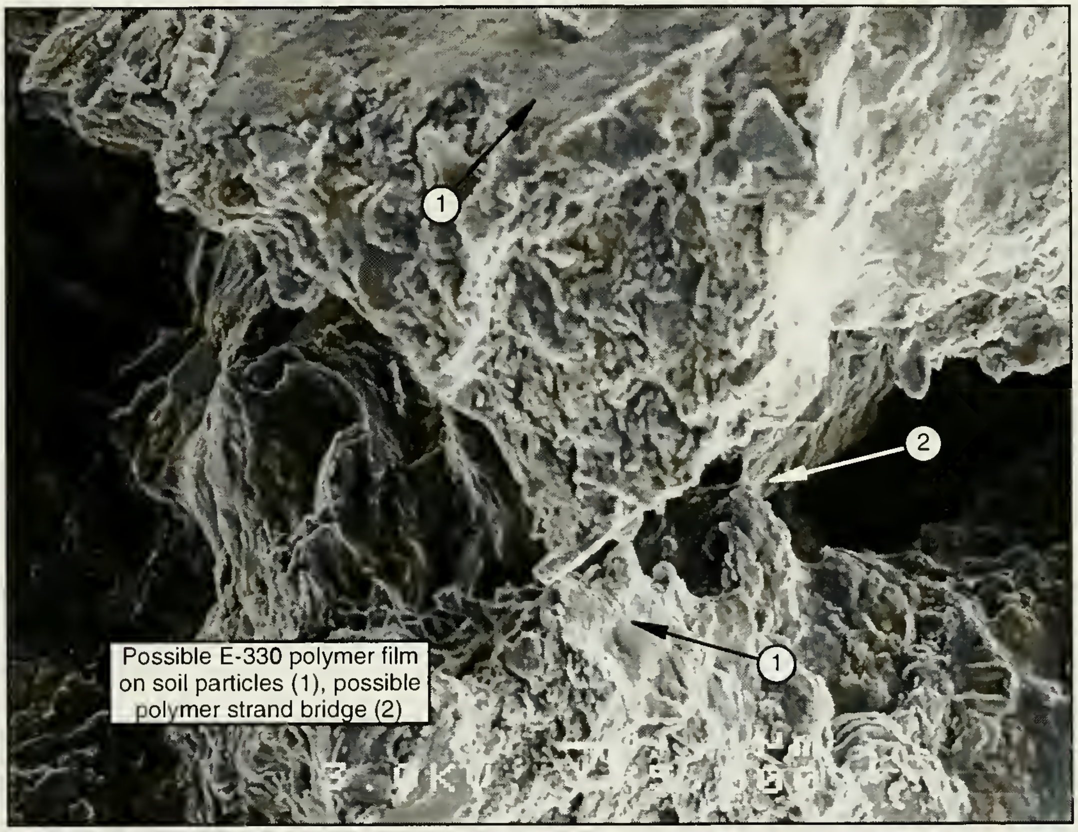


Figure 33. Butterbaugh amended adobe, 25% E-330, 5,000x magnification. Distinct polymer strands, such as those seen in the Mesa Verde soils, or in Fenn's earthen mortars, were not found in Butterbaugh's adobe soil. Because the polymer adhered the soil grains so well, it wasn't possible to accurately measure the particle size distribution of this soil. But simple visual inspection revealed a primarily sandy mix, with sharp-edged particles. The soil probably shrank very little while drying. White bar is 1 μm.

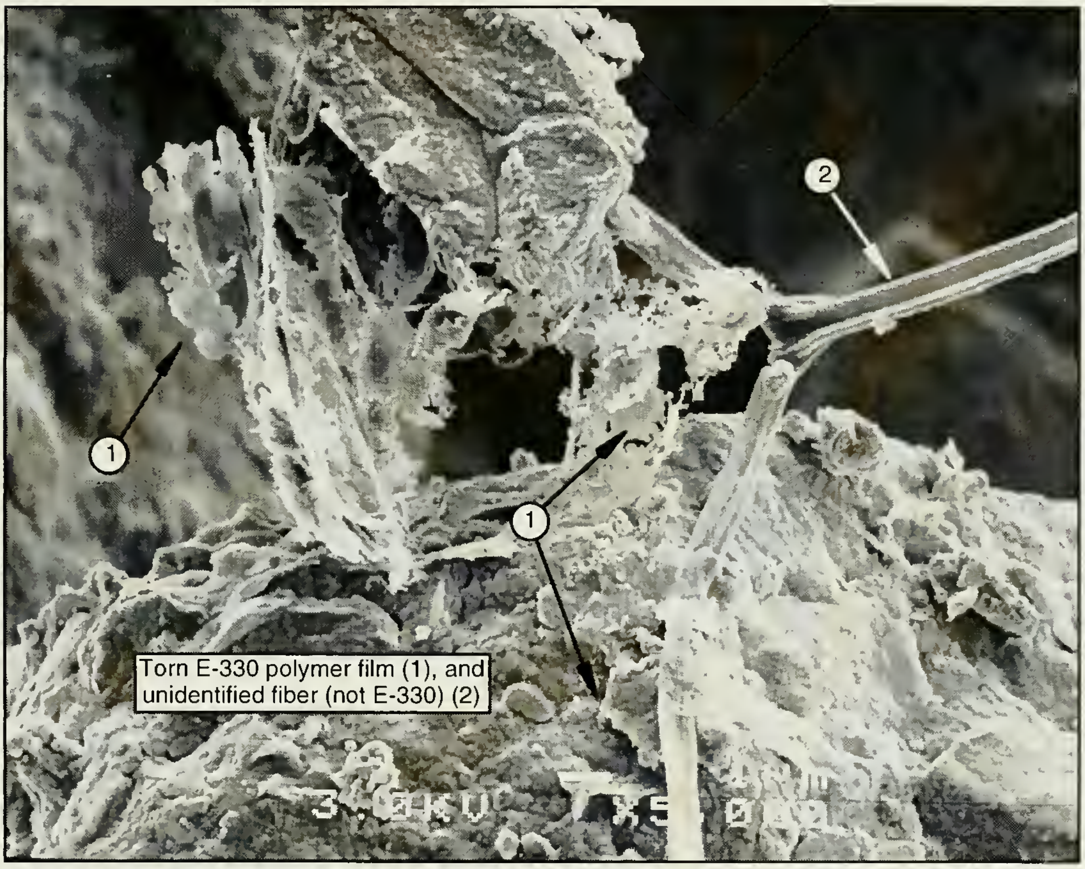


Figure 34. Long House Ruin amended earthen mortar, Mesa Verde, 5,000x magnification This deteriorated amended mortar was sampled from Long House, a cliff dwelling on Wetherill Mesa. The mortar there has a larger proportion of crusher fines, a sandier mix than that used on the mesa tops. Still, the mortar exhibited the flaking characteristic of Mesa Verde amended mortars. The damaged E-330 film is visible in the microphotograph. (The mortar contains between 25% and 33% E-330.) White bar is 1 µm.

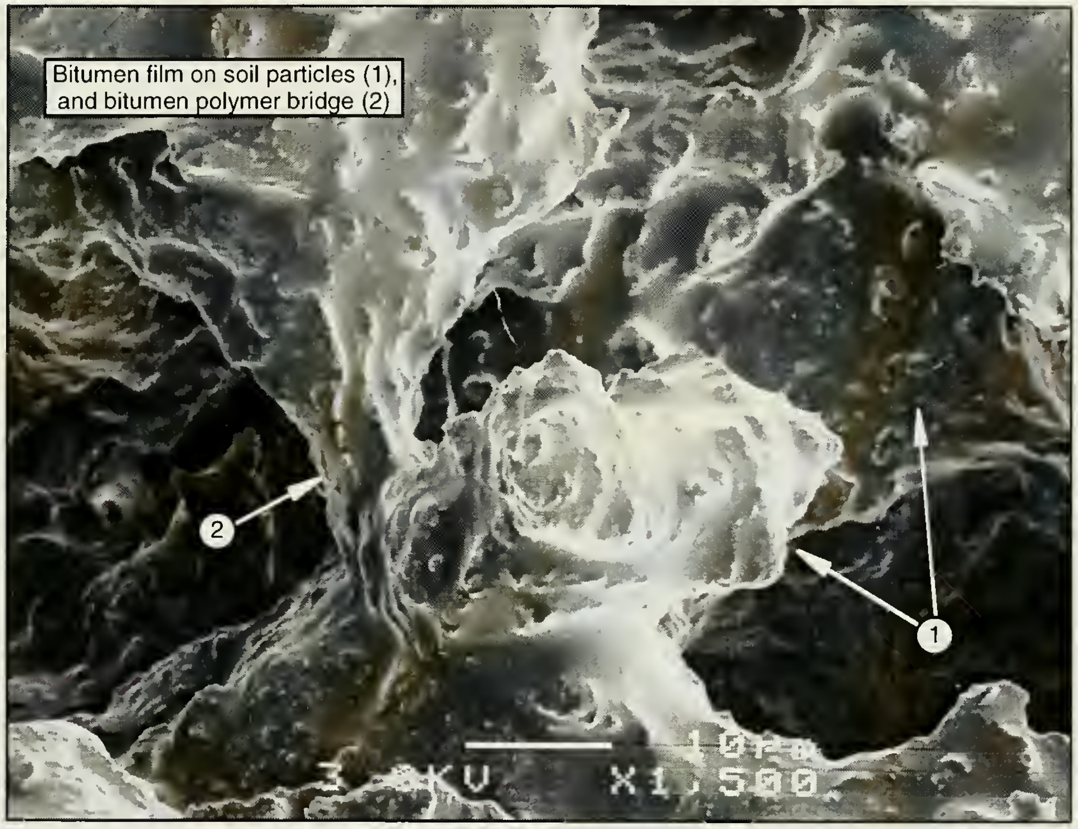
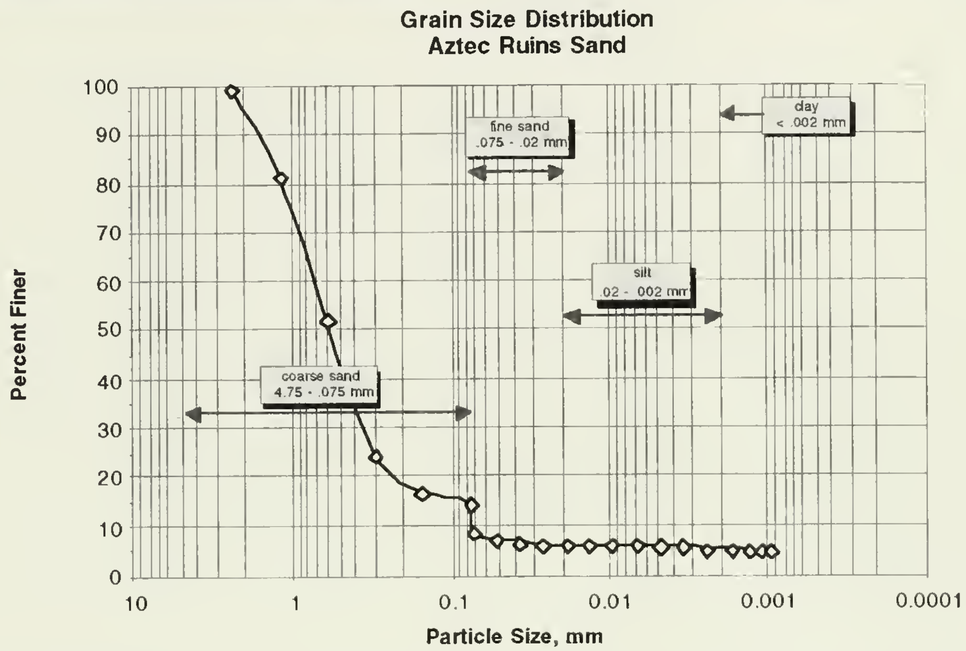


Figure 35. Bitumen-amended earthen mortar, Aztec Ruins, 1,500x magnification. This bitumen-modified earthen mortar sample was taken from early stabilization work at Aztec Ruins. The bitumen forms a much thicker coating around the soil particles than does E-330. It works by binding the particles together with a hydrophobic medium. Bitumen is the primary stabilizing ingredient used in commercial amended adobes. Compare this relatively low magnification image with any of the E-330-amended earthen mortar photomicrographs. (The percentage of bitumen in the mortar is unknown.) White bar is 10 μm.

Appendix B

Individual Soil Characterization Data

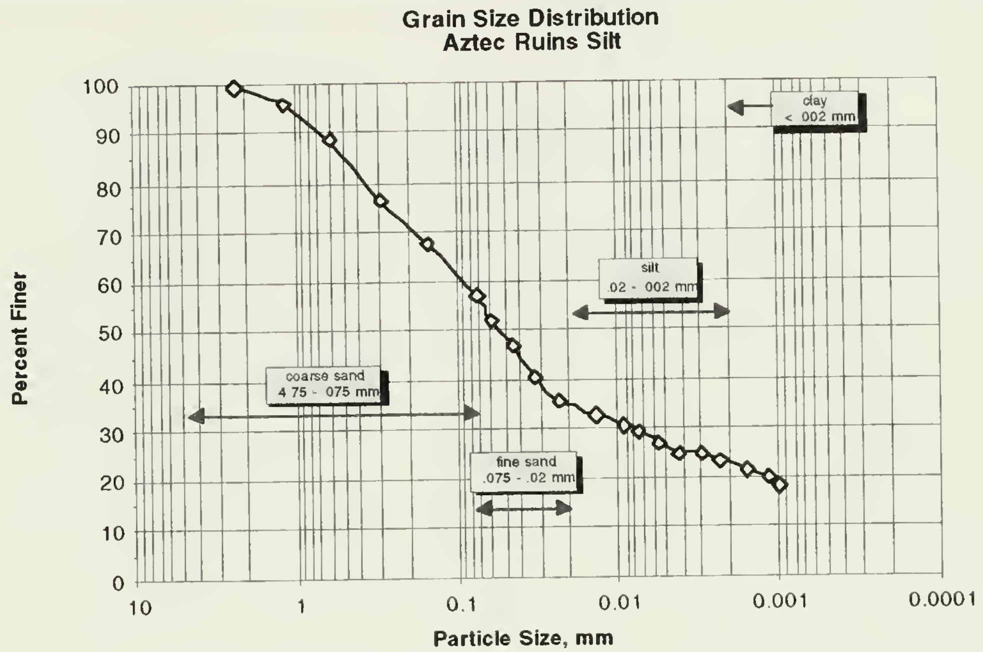
Soil Characterization Sheet	Aztec Ruins Sand



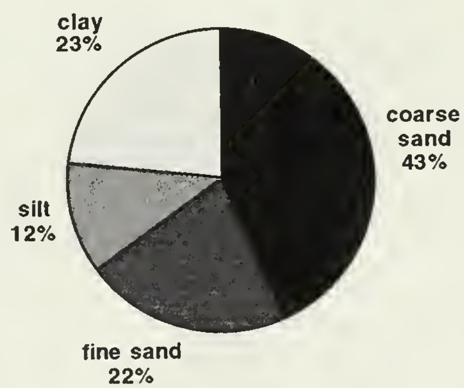
Plastic Limit	indeterminate
Liquid Limit	indeterminate
Plasticity Index	NP
Linear Shrinkage	0%
Volumetric Shrinkage	0%
pH (water/$CaCl_2$)	7.5-7.6 / 7.3
Munsell Color: dry	10YR 5/3
moist	10YR 4/4
Percent Carbonate	negligible
Soluble Salts	negligible
Soil Density	2.65 g/cm^3

Particle Description	(> 0.075 mm)
Particle Size	A well-graded sand, with almost 90% of the coarse sand fairly evenly distributed in the range between 0.300-2.36 mm
Particle Shape	Composed primarily of angular grains, low-to-medium sphericity
Color	Primarily white, quartz-like grains, with a small fraction of black, yellow grains
Notes	Almost no organic material

Soil Characterization Sheet	Aztec Ruins Silt

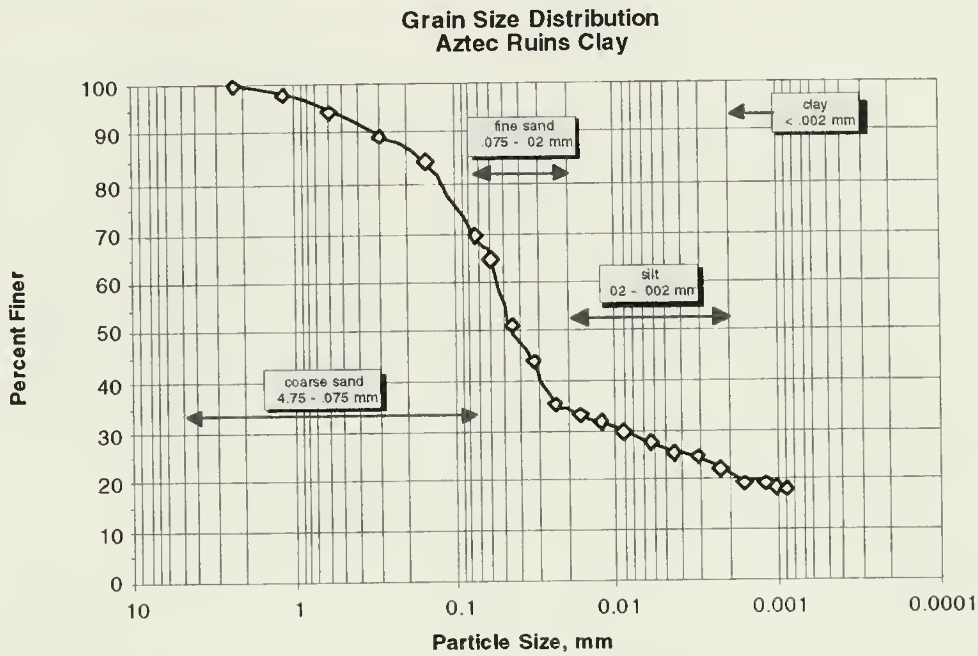


Plastic Limit	18.0
Liquid Limit	25.4
Plasticity Index	7.4
Linear Shrinkage	4.3%
Volumetric Shrinkage	19.0%
pH (water/$CaCl_2$)	7.5 / 7.2
Munsell Color: dry	10YR 5/3
moist	10YR 3/3
Percent Carbonate	3.3%
Soluble Salts	negligible
Soil Density	2.70 g/cm^3

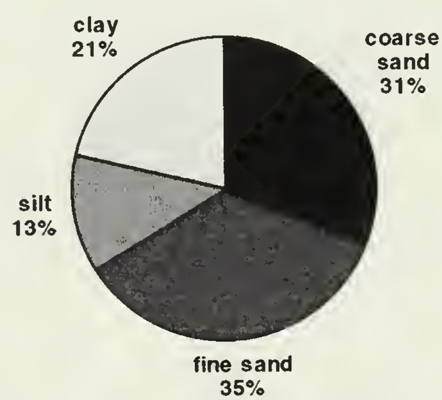


Particle Description	(> 0.075 mm)
Particle Size	More than 90% of the coarse sand portion is evenly distributed in the range between 0.075-1.18 mm
Particle Shape	Almost all the grains are angular, medium sphericity
Color	White, quartz-like, with a small fraction of black grains
Notes	Trace of fine, woody fibers

Soil Characterization Sheet	Aztec Ruins Clay

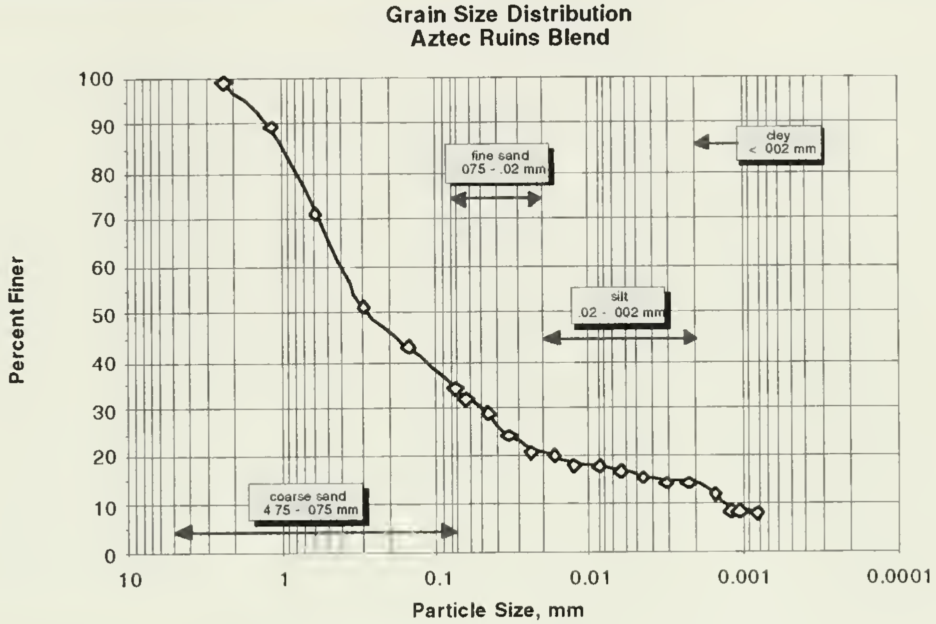


Plastic Limit	18.0
Liquid Limit	25.4
Plasticity Index	7.4
Linear Shrinkage	5.6%
Volumetric Shrinkage	18.6%
pH (water/$CaCl_2$)	7.7 / 7.3
Munsell Color: dry	10YR 5.5/3
moist	10YR 4/3
Percent Carbonate	4.6%
Soluble Salts	negligible
Soil Density	2.64 g/cm^3

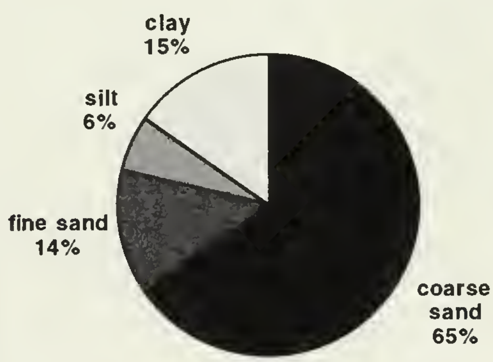


Particle Description	(> 0.075 mm)
Particle Size	Almost half the grains are in the fine end of this size range, 0.075-0.150 mm
Particle Shape	Primarily angular grains, low-to-medium sphericity
Color	White, quartz-like; few black, orange and pink grains, particularly in the coarser range
Notes	Trace of fine, woody fibers

Soil Characterization Sheet	Aztec Ruins Blend*



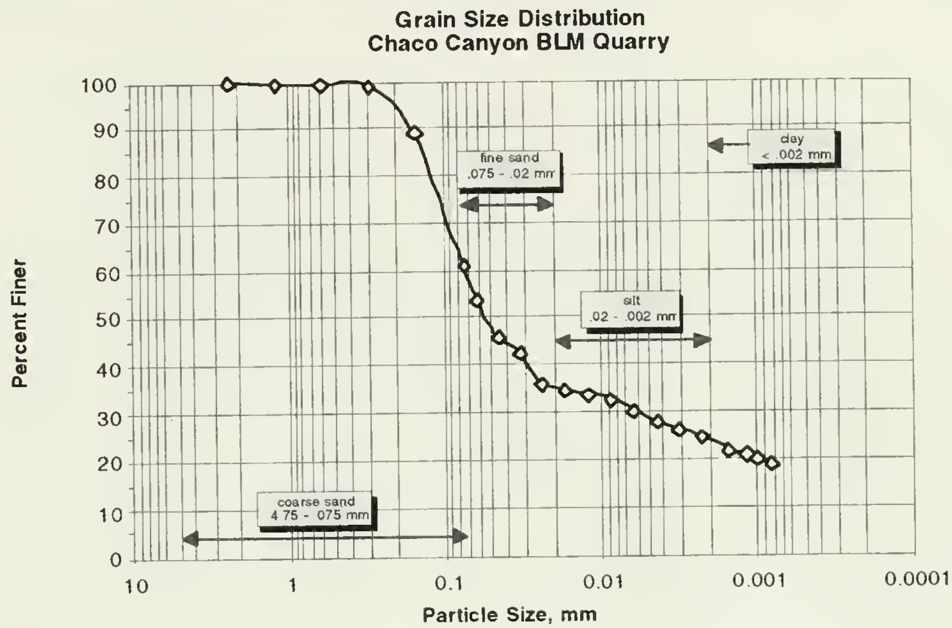
Plastic Limit	16.7
Liquid Limit	23.8
Plasticity Index	7.1
Linear Shrinkage	3.5%
Volumetric Shrinkage	9.2%
pH (water/$CaCl_2$)	7.6-7.7 / 7.3
Munsell Color: dry	10YR 5.5/3
moist	10YR 3/3
Percent Carbonate	2.4%
Soluble Salts	negligible
Soil Density	2.66 g/cm^3



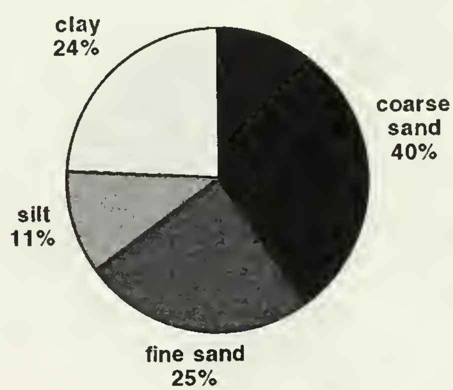
Particle Description	(> 0.075 mm)
Particle Size	(Soil is a 6:2:3 blend of Aztec Ruins Sand:Silt:Clay)
Particle Shape	
Color	
Notes	

*This soil was used as a component of earthen mortar in this research

Soil Characterization Sheet	Chaco Canyon BLM Quarry*



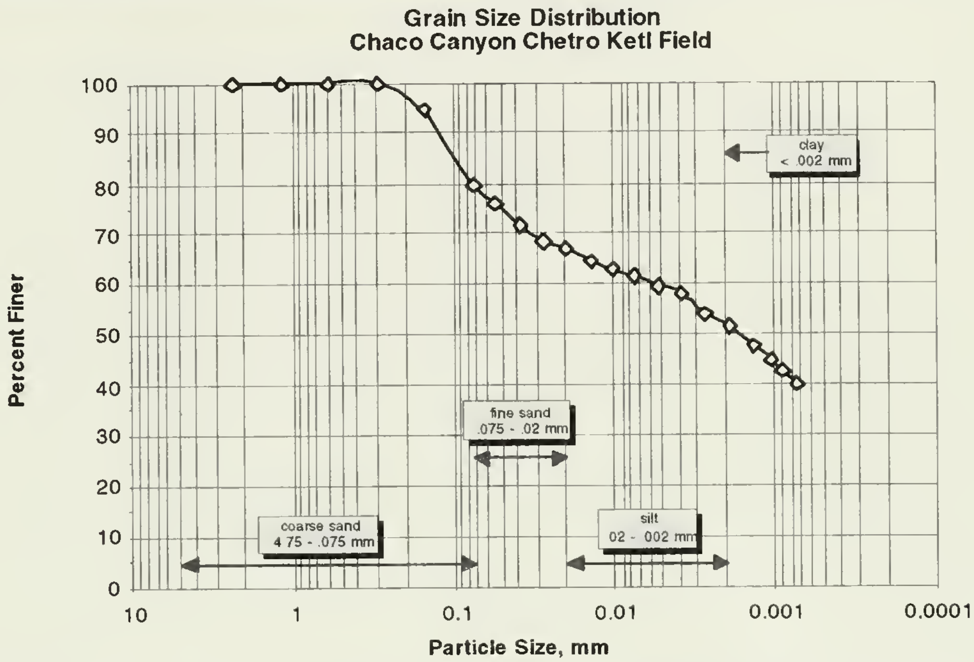
Plastic Limit	indeterminate
Liquid Limit	19.5
Plasticity Index	NP
Linear Shrinkage	4.9%
Volumetric Shrinkage	15.4%
pH (water/$CaCl_2$)	8.2 / 7.8
Munsell Color: dry	10YR 4.5/3
moist	10YR 4/3.5
Percent Carbonate	3.8%
Soluble Salts	negligible
Soil Density	2.67 g/cm^3



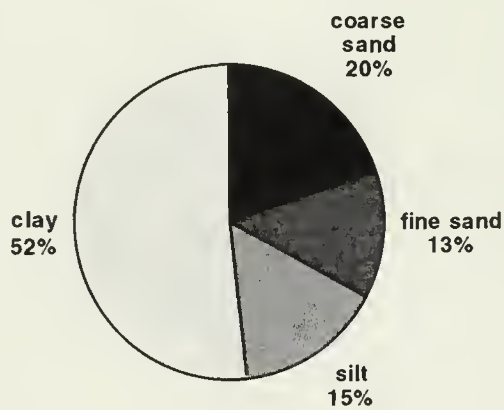
Particle Description	(> 0.075 mm)
Particle Size	26% in the range 0.150-0.300 mm, 74% in the range 0.075-0.150 mm
Particle Shape	Angular, medium-to-high sphericity
Color	Yellowish-white, quartz-like grains, few black, gray grains
Notes	Trace of woody fibers

***This soil was used as a component of earthen mortar in this research**

Soil Characterization Sheet	Chaco Canyon Chetro Ketl Field

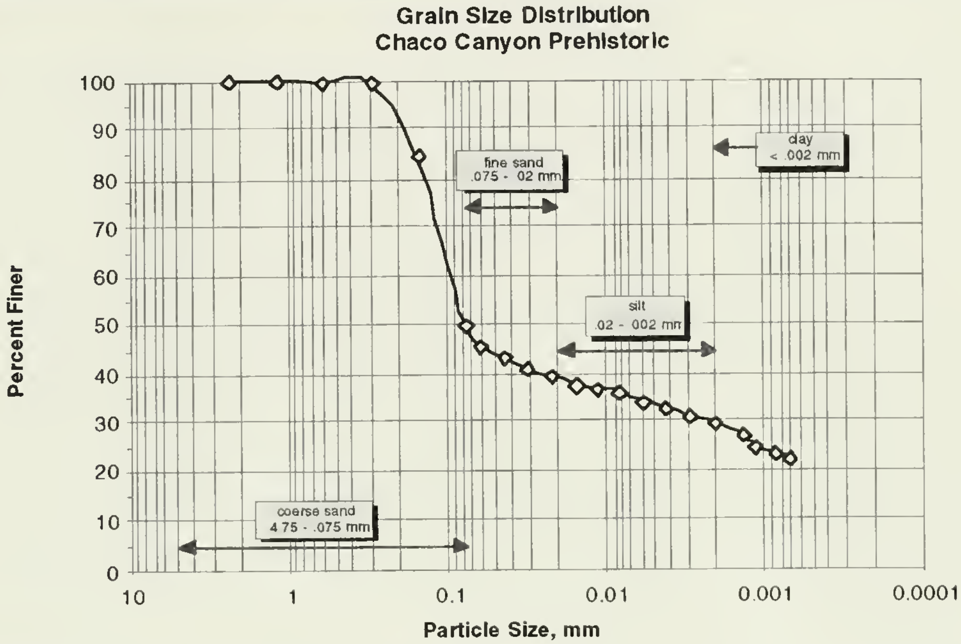


Plastic Limit	17.1
Liquid Limit	35.5
Plasticity Index	18.4
Linear Shrinkage	12.3%
Volumetric Shrinkage	24.5%
pH (water/$CaCl_2$)	8.1 / 7.7
Munsell Color: dry	10YR 4.5/3
moist	10YR 4/3
Percent Carbonate	3.9%
Soluble Salts	negligible
Soil Density	2.75 g/cm^3

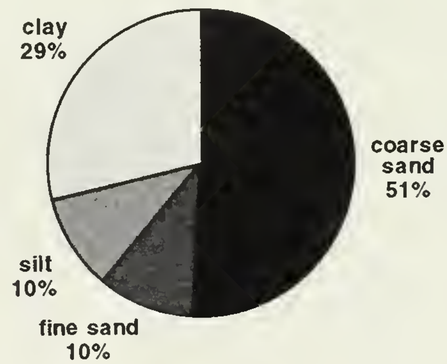


Particle Description	(> 0.075 mm)
Particle Size	26% in the range 0.150-0.300 mm, 74% in the range 0.075-0.150 mm
Particle Shape	Angular, medium sphericity
Color	White, quartz-like, with few black grains
Notes	No significant organic matter, some calcite particles

Soil Characterization Sheet	Chaco Canyon Chetro Ketl Prehistoric

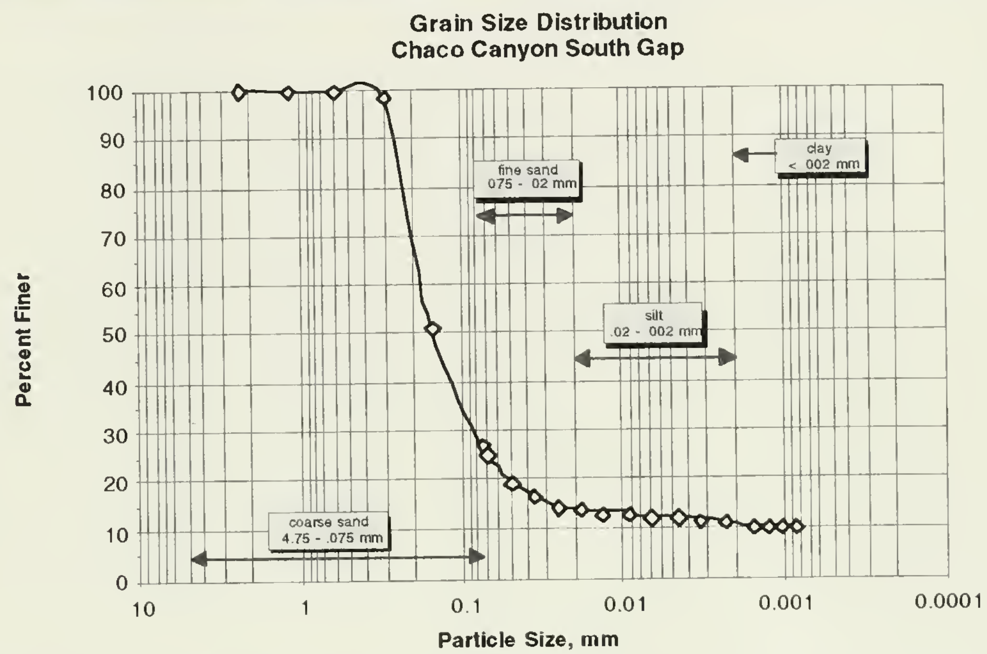


Plastic Limit	15.7
Liquid Limit	23.3
Plasticity Index	7.6
Linear Shrinkage	6.6%
Volumetric Shrinkage	18.6%
pH (water/$CaCl_2$)	8.3 / 7.7
Munsell Color: dry	10YR 5/4
moist	10YR 4/4
Percent Carbonate	5.1%
Soluble Salts	negligible
Soil Density	2.71 g/cm^3

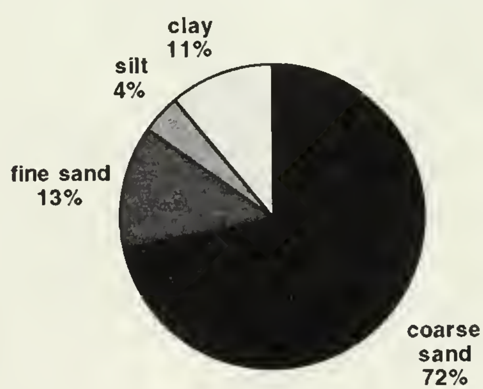


Particle Description	(> 0.075 mm)
Particle Size	30% in the range 0.150-0.300 mm, 70% in the range 0.075-0.150 mm
Particle Shape	Angular, low-to-medium sphericity
Color	White, yellowish-white, quartz-like grains, few black, pink grains
Notes	No significant organic matter

Soil Characterization Sheet	Chaco Canyon South Gap

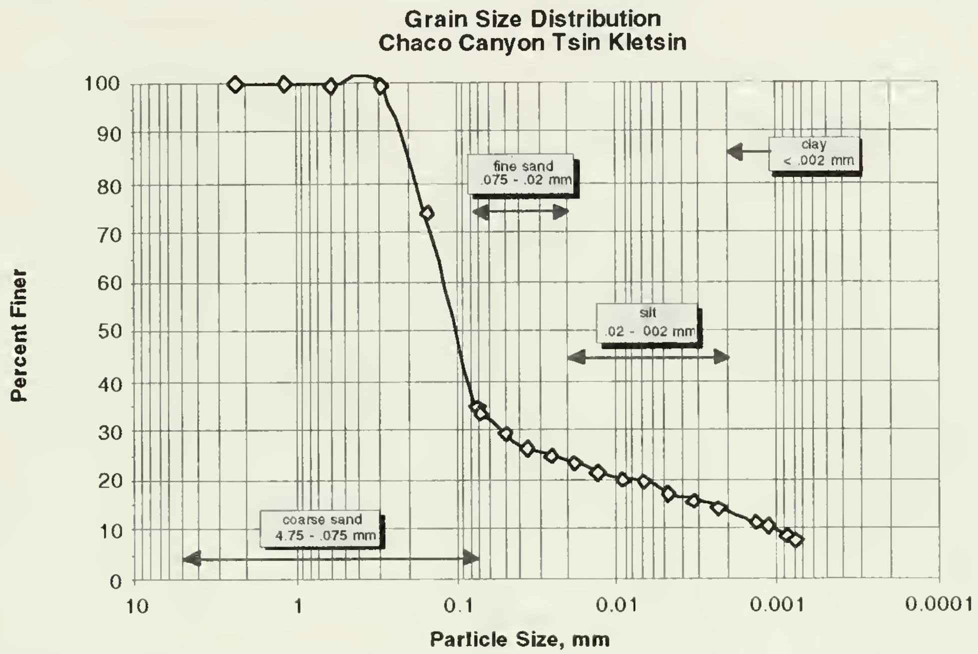


Plastic Limit	indeterminate
Liquid Limit	indeterminate
Plasticity Index	NP
Linear Shrinkage	0.4%
Volumetric Shrinkage	5.13%
pH (water/$CaCl_2$)	7.7 / 7.4-7.5
Munsell Color: dry	10YR 5/2.5
moist	10YR 3.5/3
Percent Carbonate	2.2%
Soluble Salts	negligible
Soil Density	2.66 g/cm^3

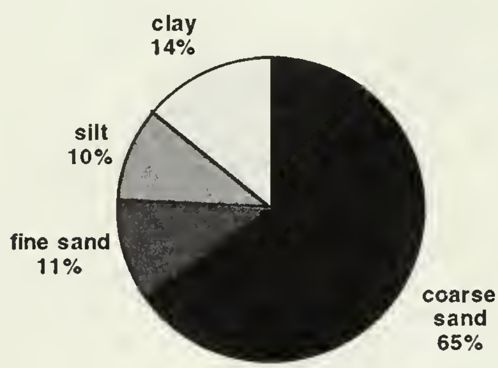


Particle Description	(> 0.075 mm)
Particle Size	33% in the range 0.150-0.300 mm, 67% in the range 0.075-0.150 mm
Particle Shape	Predominately angular, low to medium sphericity, few fine sub-angular grains with medium-to-high sphericity
Color	Yellowish-white quartz-like grains, few orange, black, yellow grains
Notes	Some fine woody fibers, some calcite particles

Soil Characterization Sheet	Chaco Canyon Tsin Kletsin

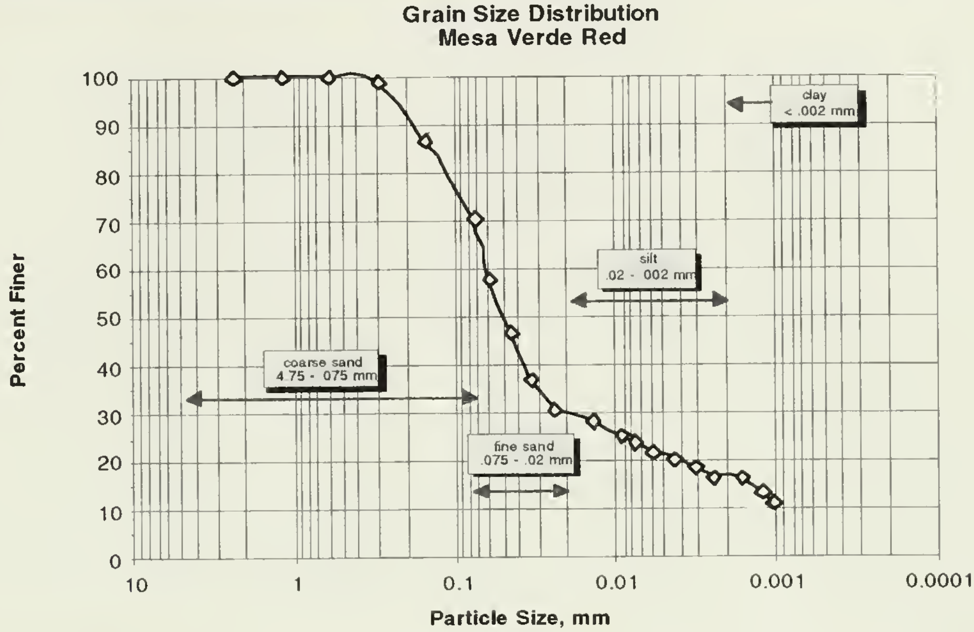


Plastic Limit	indeterminate
Liquid Limit	16.3
Plasticity Index	NP
Linear Shrinkage	2.5%
Volumetric Shrinkage	7.0%
pH (water/$CaCl_2$)	7.8 / 7.4
Munsell Color: dry	10YR 6/3.5
moist	10YR 3.5/3
Percent Carbonate	2.5%
Soluble Salts	negligible
Soil Density	2.68 g/cm^3

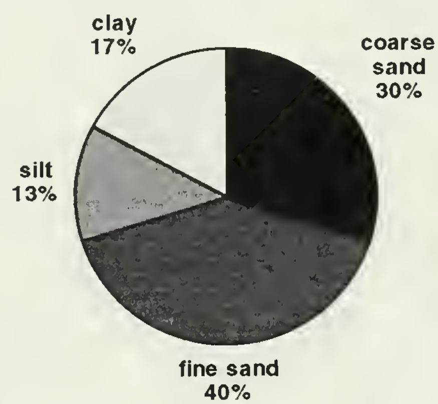


Particle Description	(> 0.075 mm)
Particle Size	40% in the range 0.150-0.300 mm, 60% in the range 0.075-0.150 mm
Particle Shape	Angular grains, medium and low-to-medium sphericity
Color	White, quartz-like, few black, orange grains
Notes	Few fine fibers, some calcite particles

Soil Characterization Sheet	Mesa Verde Red

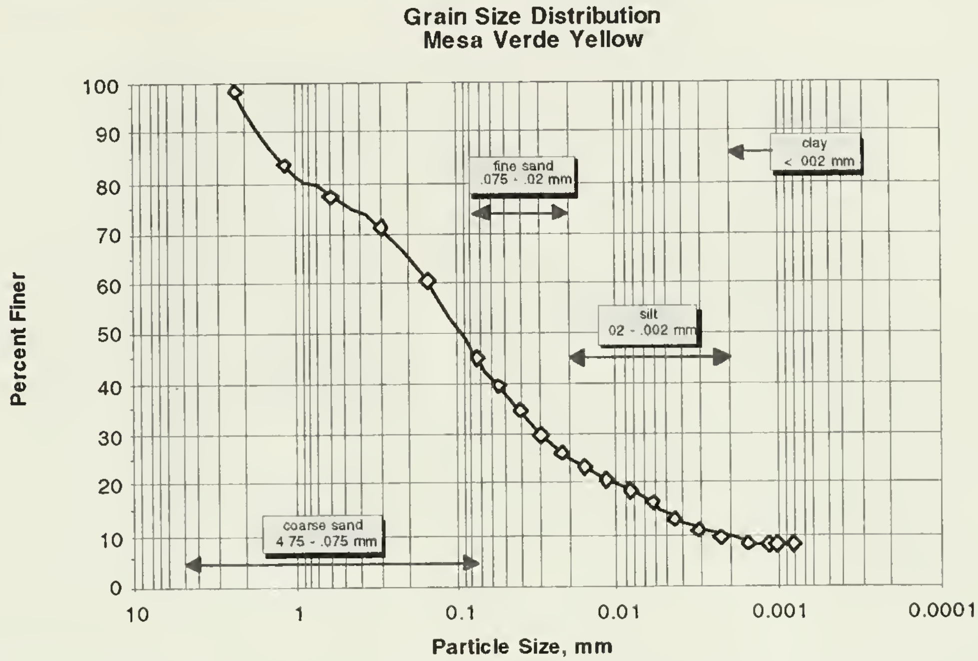


Plastic Limit	19.3
Liquid Limit	22.2
Plasticity Index	2.9
Linear Shrinkage	5.6%
Volumetric Shrinkage	16.9%
pH (water/$CaCl_2$)	7.6 / 7.4
Munsell Color: dry	7.5YR 4/5
moist	7.5YR 3/4
Percent Carbonate	3.4%
Soluble Salts	negligible
Soil Density	2.66 g/cm^3

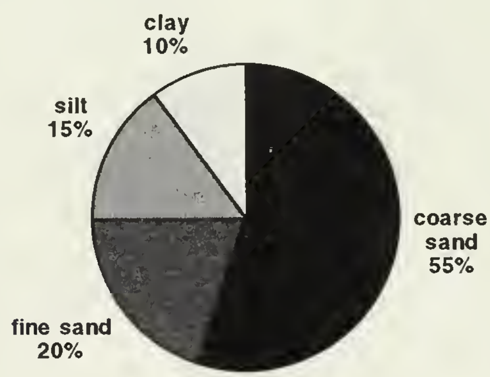


Particle Description:	(> 0.075 mm)
Particle Size	More than 90% of the grains are between 0.075 and 0.300 mm
Particle Shape	Angular, low-to-medium sphericity
Color	Predominantly white, quartz-like, grains; some black, orange grains
Notes	A trace of woody fibers; some calcite visible in all particle size ranges

Soil Characterization Sheet	Mesa Verde Yellow

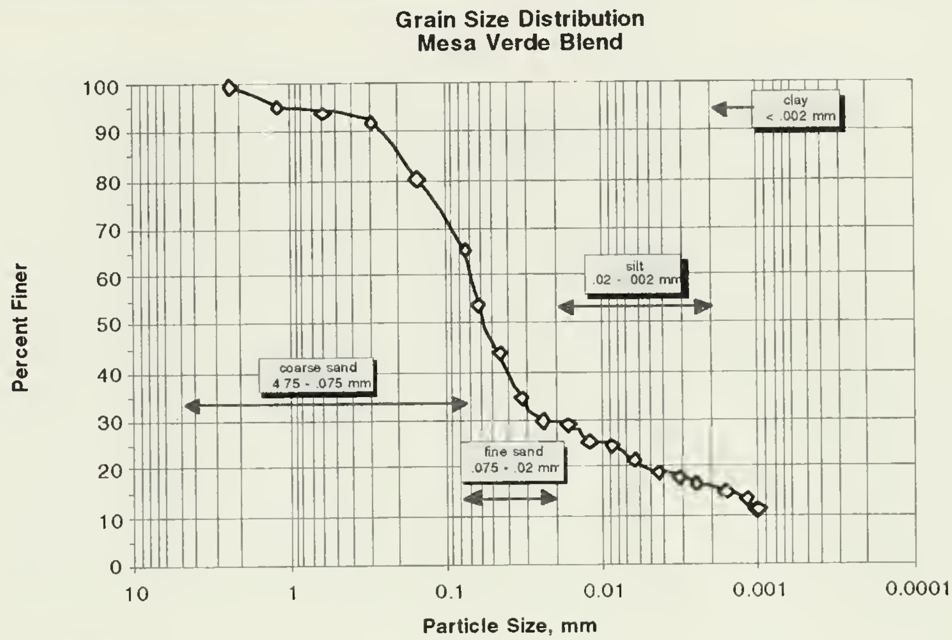


Plastic Limit	23.4
Liquid Limit	27.5
Plasticity Index	4.1
Linear Shrinkage	2.5%
Volumetric Shrinkage	9.3%
pH (water/$CaCl_2$)	8.2 / 7.7
Munsell Color: dry	10YR 6.5/4
moist	10YR 5/6
Percent Carbonate	22.6%
Soluble Salts	negligible
Soil Density	2.75 g/cm^3

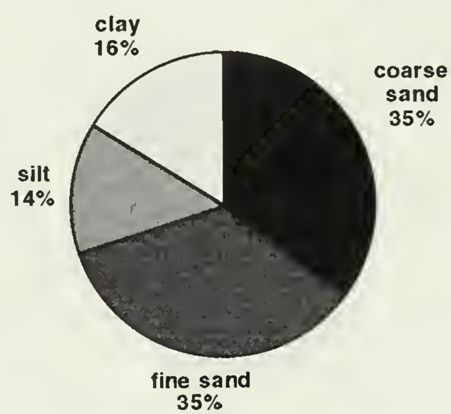


Particle Description	(> 0.075 mm)
Particle Size	Grains distributed throughout the range of 0.075 to 2.36 mm.
Particle Shape	Predominately angular with low-to-medium sphericity; some of the larger grains are collections of smaller particles, cemented with calcite
Color	Larger grains are varied, black, gray, red, yellow, all coated with yellow-orange calcite; smaller grains are predominately white, quartz-like, with a few black, orange, red grains
Notes	No significant organic matter; calcite present throughout

Soil Characterization Sheet	Mesa Verde Blend*



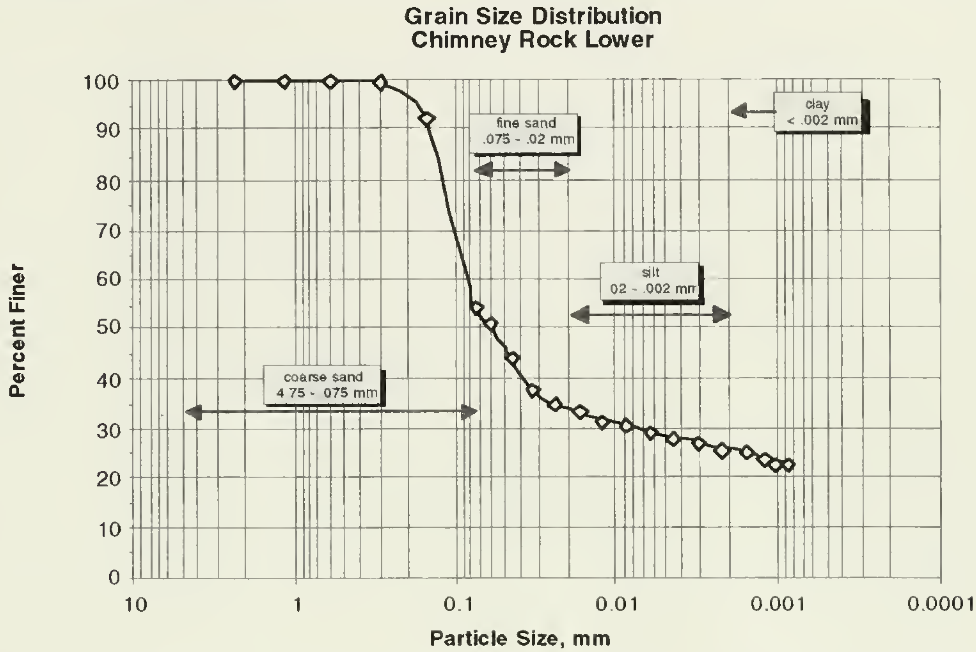
Plastic Limit	19.2	
Liquid Limit	21.9	
Plasticity Index	2.7	
Linear Shrinkage	4.6%	
Volumetric Shrinkage	11.3%	
pH (water/$CaCl_2$)	7.7 / 7.5	
Munsell Color: dry	7.5YR 5/4	
moist	7.5YR 3.5/5	
Percent Carbonate	8.1%	
Soluble Salts	negligible	
Soil Density	2.70 g/cm^3	



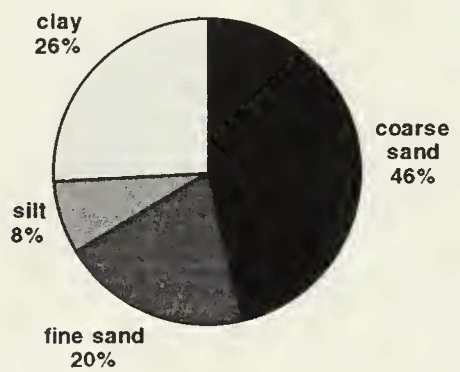
Particle Description	(> 0.075 mm)
Particle Size	(Soil is a 2:1 blend of Mesa Verde Red:Mesa Verde Yellow)
Particle Shape	
Color	
Notes	

*This soil was used as a component of earthen mortar in this research

Soil Characterization Sheet	Chimney Rock Lower

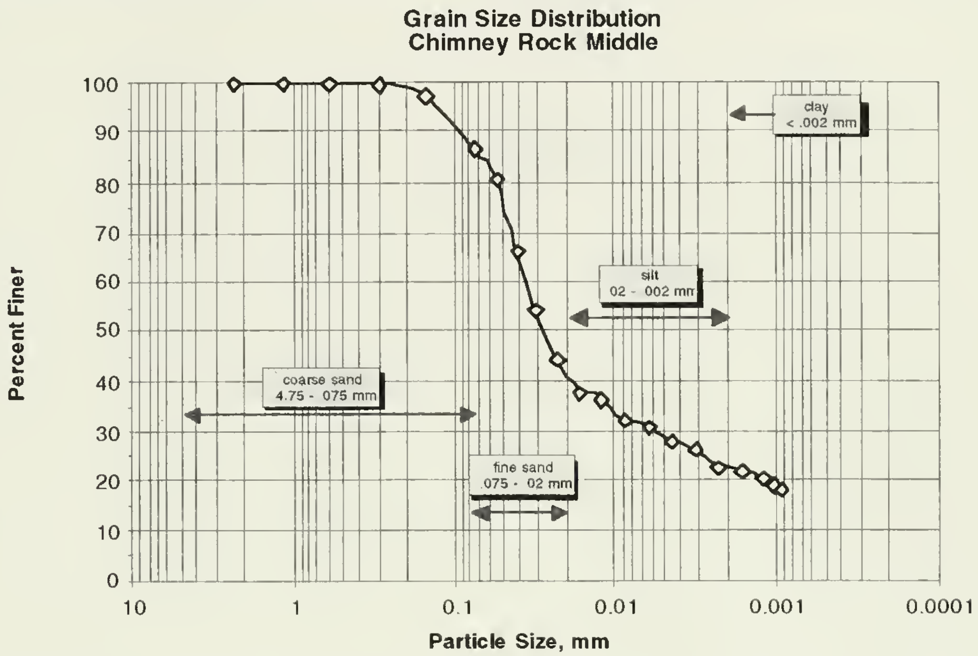


Plastic Limit	16.9
Liquid Limit	23.7
Plasticity Index	6.8
Linear Shrinkage	5.4%
Volumetric Shrinkage	16.6%
pH (water/$CaCl_2$)	7.0-7.1 / 6.7
Munsell Color: dry	10YR 5/4
moist	10YR 3/4
Percent Carbonate	8.1%
Soluble Salts	negligible
Soil Density	negligible

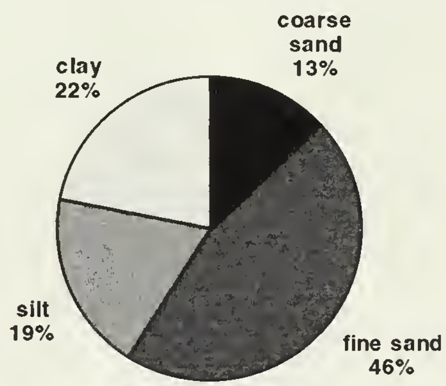


Particle Description	(> 0.075 mm)
Particle Size	Almost 84% of the grains are very fine, in the range 0.075-0.150 mm
Particle Shape	Predominately angular, medium sphericity
Color	White, quartz-like; some black, brown, orange and red grains
Notes	Trace of fine organic matter

Soil Characterization Sheet	Chimney Rock Middle

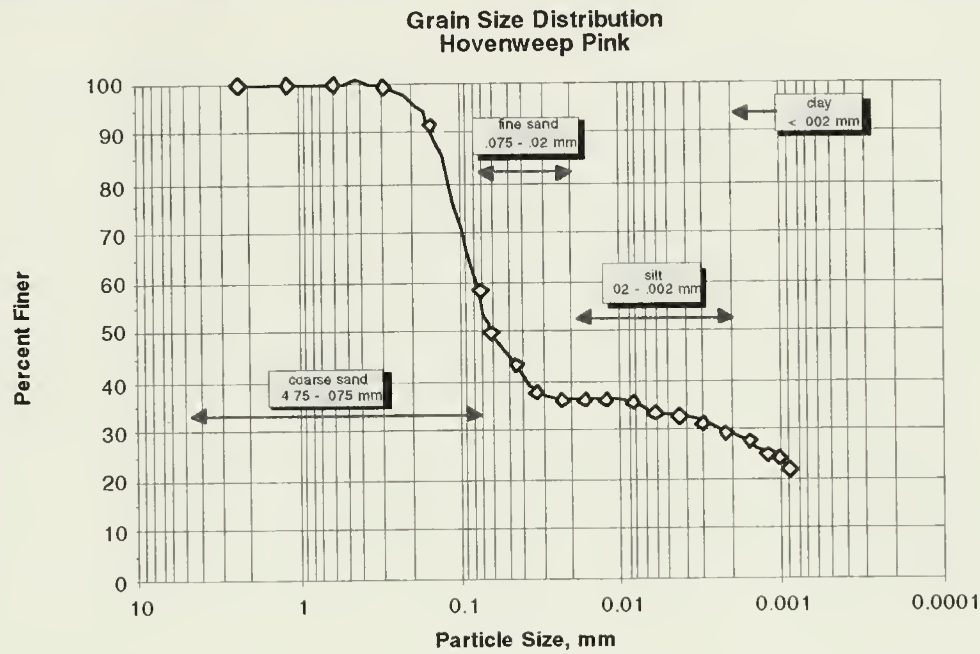


Plastic Limit	18.3
Liquid Limit	19.5
Plasticity Index	1.2
Linear Shrinkage	3.7%
Volumetric Shrinkage	14.0%
pH (water/$CaCl_2$)	6.9-7.0 / 6.5
Munsell Color: dry	10YR 5/3.5
moist	10YR 3/3
Percent Carbonate	negligible
Soluble Salts	negligible
Soil Density	2.69 g/cm^3

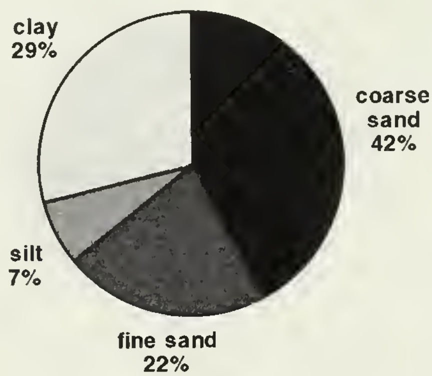


Particle Description	(> 0.075 mm)
Particle Size	Almost 82% of the grains are very fine, in the range 0.075-0.150 mm
Particle Shape	Angular, medium-to-high sphericity
Color	Yellowish-white, quartz-like grains; some black, orange and red grains
Notes	Some fine, woody fibers, primarily in the larger size ranges

Soil Characterization Sheet	Hovenweep Pink

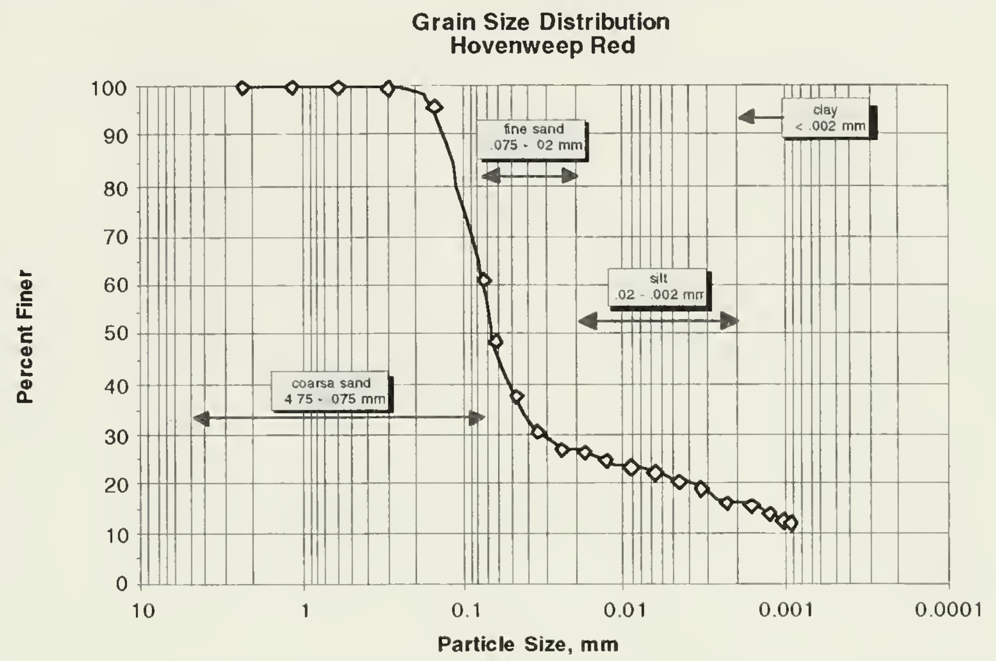


Plastic Limit	16.5
Liquid Limit	18.7
Plasticity Index	22.2
Linear Shrinkage	4.9%
Volumetric Shrinkage	14.8%
pH (water/$CaCl_2$)	7.7-7.8 / 7.3
Munsell Color: dry	5YR 6/4
moist	5YR 4/6
Percent Carbonate	21.3%
Soluble Salts	negligible
Soil Density	2.69 g/cm^3

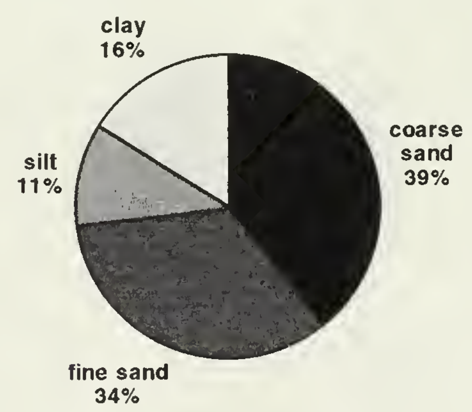


Particle Description	(> 0.075 mm)
Particle Size	Nearly all the grains are finer than 0.300 mm, and 81% of the sample is in the range of 0.075-0.150 mm
Particle Shape	Predominately angular, medium and medium-to-high sphericity
Color	White, quartz-like; some black, orange grains
Notes	Trace of woody fibers, trace of calcite particles

Soil Characterization Sheet	Hovenweep Red

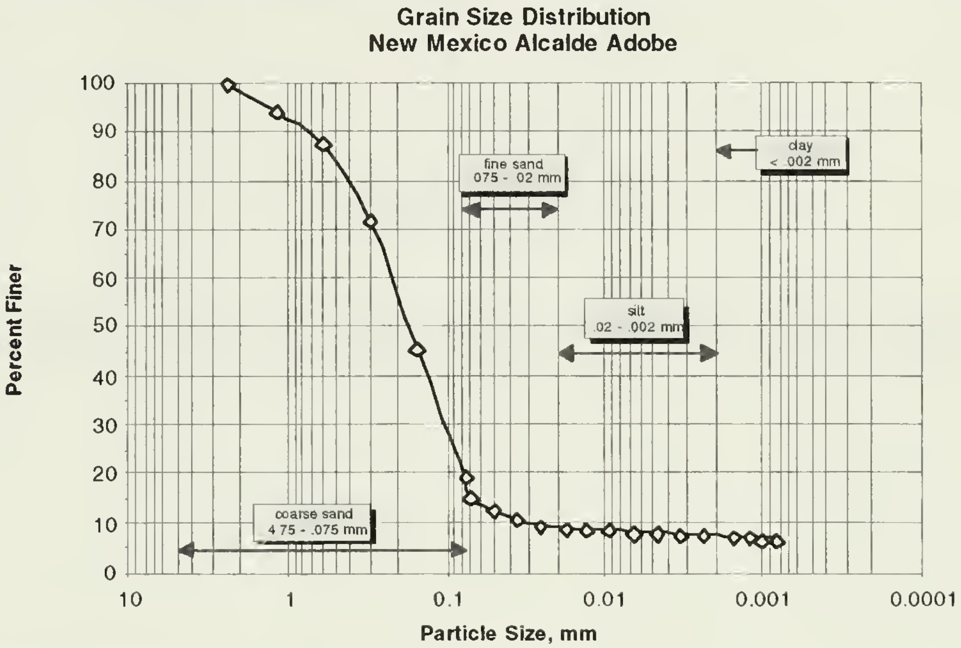


Plastic Limit	17.7
Liquid Limit	19.9
Plasticity Index	2.2
Linear Shrinkage	3.5%
Volumetric Shrinkage	11.8%
pH (water/$CaCl_2$)	7.9 / 7.7
Munsell Color: dry	5YR 4/6
moist	5YR 3/4
Percent Carbonate	2.6%
Soluble Salts	negligible
Soil Density	2.67 g/cm^3

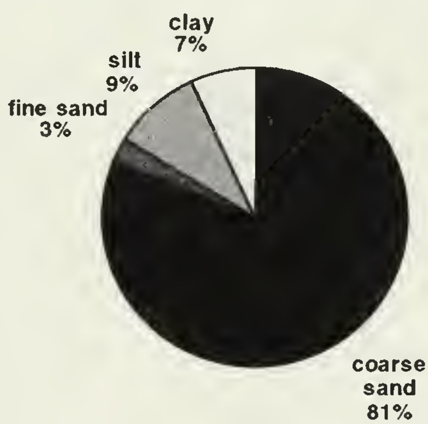


Particle Description	(> 0.075 mm)
Particle Size	90% of the grains are in the range of 0.075-0.150 mm
Particle Shape	Angular, medium-to-high sphericity
Color	Pale orange grains, quartz-like
Notes	Trace of woody fibers

Soil Characterization Sheet	New Mexico Alcalde Adobe*



Plastic Limit	indeterminate
Liquid Limit	indeterminate
Plasticity Index	NP
Linear Shrinkage	0.4%
Volumetric Shrinkage	3.3%
pH (water/$CaCl_2$)	7.6-7.7 / 7.3
Munsell Color: dry	10YR 6/3
moist	10YR 4/3
Percent Carbonate	3.9%
Soluble Salts	negligible
Soil Density	2.69 g/cm^3



Particle Description	(> 0.075 mm)
Particle Size	A fine sandy soil, more than 50% of the grains are in the range of 0.075-0.300 mm
Particle Shape	Angular, low-to-medium sphericity
Color	Predominately white, quartz-like; some pink and orange grains
Notes	No significant organic matter; flat, brown, transparent plates in the finest fraction: some calcite in the larger size ranges

***This soil was used as a component of earthen mortar in this research**

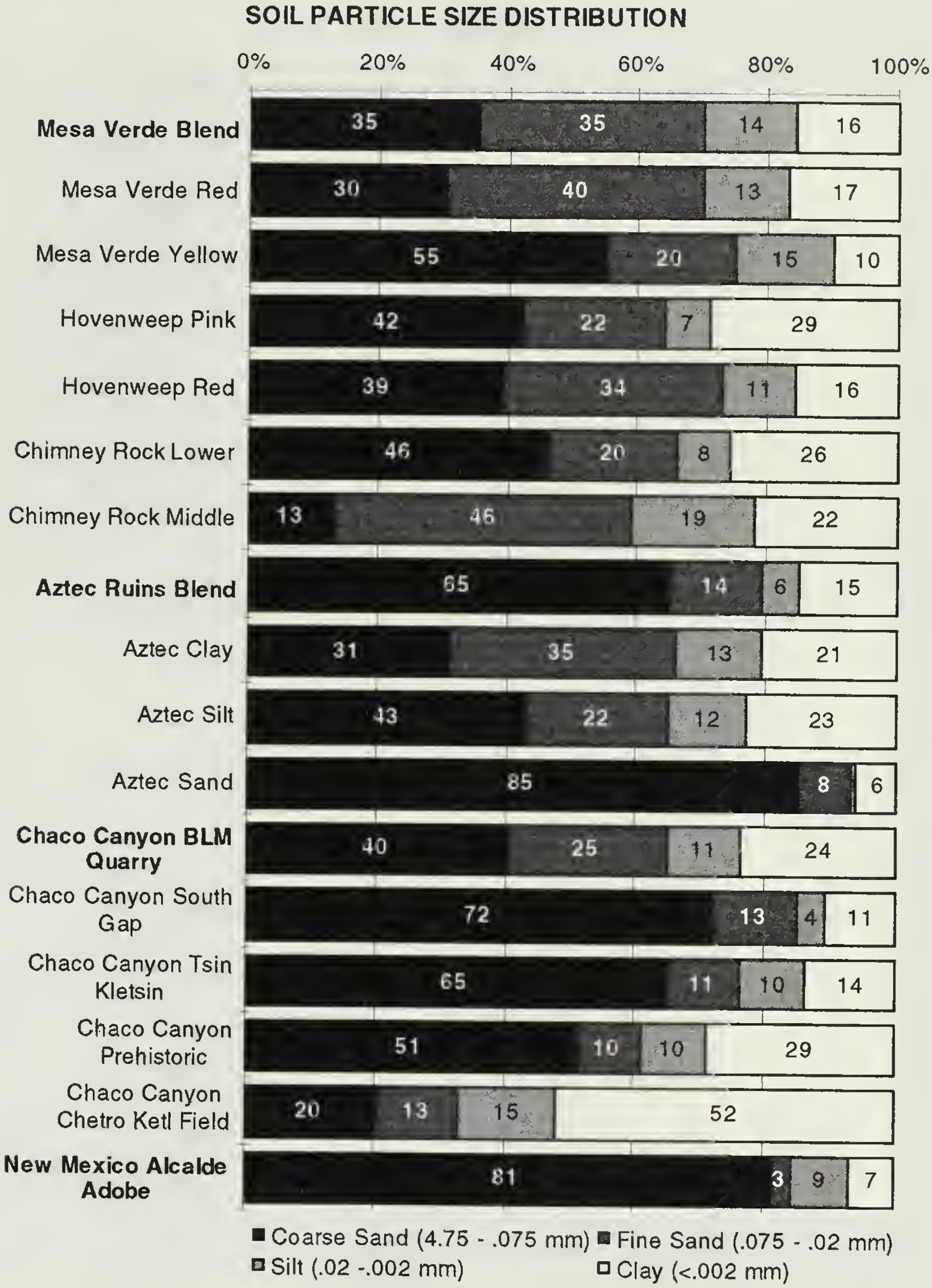
Appendix C

Soil Characterization Summary Data

Soil Characterization Tests and Observations and Applicable Standards Used

(Details of the soil characterization program are described in Chapter 4)

1. Munsell color characterization (dry and moist)
   - *ASTM D1535, Standard Test Method for Specifying Color by the Munsell System*
2. Determination of soil pH
   - *ASTM D4972, Standard Test Method for pH of Soils*
3. Soil Particle Size Distribution, by sieving and hydrometer methods
   - *ASTM D422, Standard Test Method for Particle-Size Analysis of Soils*
   - *ASTM D653, Standard Terminology Relating to Soil, Rock, and Contained Fluids*
4. Optical microscopic examination to determine soil particle characteristics (>0.075 mm)
5. Determination of soil density
   - *ASTM D854, Standard Test Method for Specific Gravity of Soils*
6. Qualitative analysis to determine presence of soluble salts
7. Acid digestion to determine acid-soluble (carbonate) content
8. Determination of Atterberg limits (Liquid and Plastic Limits, Plasticity Index)
   - *ASTM D4318, Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*
9. Determination of Linear and Volumetric Shrinkage
   - *ASTM D4943, Standard Test Method for Shrinkage Factors of Soils by the Wax Method*
10. X-ray Diffraction analysis for qualitative and semi-quantitative clay mineralogy (selected soils)
11. Qualitative bulk mineralogical analysis (selected soils)



Soils in bold type were tested as components of soil mortar

Figure 36

SOIL DENSITY

Soil	Density (g/cm^3)
Mesa Verde Red	2.66
Mesa Verde Yellow	2.75
Mesa Verde Blend	**2.70**
Hovenweep Pink	2.69
Hovenweep Red	2.67
Lower Chimney Rock	2.69
Middle Chimney Rock	2.67
Aztec Ruins Clay	2.64
Aztec Ruins Silt	2.70
Aztec Ruins Sand	2.65
Aztec Ruins Blend	**2.66**
Chaco Canyon South Gap	2.66
Chaco Canyon BLM Quarry	**2.67**
Chaco Canyon Tsin Kletsin	2.68
Chaco Canyon Chetro Ketl Field	2.75
Chaco Canyon Chetro Ketl Prehistoric	2.71
New Mexico Alcalde Adobe	**2.69**

Soils in bold type were tested as components in earthen mortars

Figure 16

As a comparison, following is a list of common minerals and their specific gravity (From Das, 1979):

MINERAL DENSITY

Mineral	Density (g/cm^3)
Quartz	2.65
Kaolinite	2.6
Illite	2.8
Montmorillonite	2.65 to 2.8
Halloysite	2.0 to 2.55
K feldspar	2.57
Na and Ca feldspar	2.62 to 2.76
Chlorite	2.6 to 2.9
Biotite	2.8 to 3.2
Muscovite	2.76 to 3.1
Hornblende	3.0 to 3.47
Limonite	3.6 to 4.0
Olivine	3.27 to 3.37

Table 17

SOIL pH

Soil	pH in Water	pH in $CaCl_2$
Mesa Verde Red	7.6	7.4
Mesa Verde Yellow	8.2	7.7
Mesa Verde Blend	**7.7**	**7.5**
Hovenweep Pink	7.7-7.8	7.3
Hovenweep Red	7.9	7.7
Lower Chimney Rock	7.0-7.1	6.7
Middle Chimney Rock	6.9-7.0	6.5
Aztec Ruins Clay	7.7	7.3
Aztec Ruins Silt	7.5	7.2
Aztec Ruins Sand	7.5-7.6	7.3
Aztec Ruins Blend	**7.6-7.7**	**7.3**
Chaco Canyon South Gap	7.7	7.4-7.5
Chaco Canyon BLM Quarry	**8.2**	**7.8**
Chaco Canyon Tsin Kletsin	7.8	7.4
Chaco Canyon Chetro Ketl Field	8.1	7.7
Chaco Canyon Chetro Ketl Prehistoric	8.3	7.7
New Mexico Alcalde Adobe	**7.6-7.7**	**7.3**

Soils in bold type were tested as components of earthen mortars

Table 18

ACID-SOLUBLE (CARBONATE) FRACTION

Soil	Percent Acid-Soluble
Mesa Verde Red	3.4%
Mesa Verde Yellow	22.6%
Mesa Verde Blend	**8.1%**
Hovenweep Pink	21.3%
Hovenweep Red	2.6%
Lower Chimney Rock	negligible
Middle Chimney Rock	negligible
Aztec Ruins Clay	4.6%
Aztec Ruins Silt	3.3
Aztec Ruins Sand	negligible
Aztec Ruins Blend	**2.4%**
Chaco Canyon South Gap	2.2%
Chaco Canyon BLM Quarry	**3.8%**
Chaco Canyon Tsin Kletsin	2.5%
Chaco Canyon Chetro Ketl Field	3.9%
Chaco Canyon Chetro Ketl Prehistoric	5.1%
New Mexico Alcalde Adobe	**3.9%**

Soils in bold type were tested as components of earthen mortars

Table 19

ATTERBERG LIMITS

Soil	Plastic Limit	Liquid Limit	Plasticity Index
Mesa Verde Red	19.3	22.2	2.9
Mesa Verde Yellow	23.4	27.5	4.1
Mesa Verde Blend	**19.2**	**21.9**	**2.7**
Hovenweep Pink	16.5	18.7	2.2
Hovenweep Red	17.7	19.9	2.2
Lower Chimney Rock	16.9	23.7	6.8
Middle Chimney Rock	18.3	19.5	1.2
Aztec Ruins Clay	17.2	24.4	7.2
Aztec Ruins Silt	18.0	25.4	7.4
Aztec Ruins Sand	Indeterminate	Indeterminate	NP*
Aztec Ruins Blend	**16.7**	**23.8**	**7.1**
Chaco Canyon South Gap	Indeterminate	Indeterminate	NP*
Chaco Canyon BLM Quarry	**Indeterminate**	**19.5**	**NP****
Chaco Canyon Tsin Kletsin	Indeterminate	16.3	NP**
Chaco Canyon Chetro Ketl Field	17.1	35.5	18.4
Chaco Canyon Chetro Ketl Prehistoric	15.7	23.3	7.6
New Mexico Alcalde Adobe	**Indeterminate**	**Indeterminate**	**NP***

Soils in bold type were tested as components of earthen mortars
NP* = non-plastic, no liquid limit, so plastic limit not attempted
NP** = non-plastic, soil broke before 3.2 mm cylinder could be formed

Table 20

QUALITATIVE ANALYSIS FOR ANIONS
(Soluble Salts)

Anion	Primary Test	Confirmation Test
Sulfates (SO_4^{2-})	• Place approximately 5 ml of test solution in a test tube • Add 1-2 drops of 0.25M BaCl • *A white ppt. indicates a positive test for sulfates*	• Place approximately 5 ml of test solution in a test tube • Add 3 drops of 0.25M lead acetate • *A white ppt. indicates a positive test for sulfates*
Chlorides (Cl^{1-})	• Place approximately 5 ml of test solution in a test tube • Add 1-2 drops of 0.1M $AgNO_3$ • *A bluish-white gelatinous ppt. indicates a positive test for chlorides*	• Place approximately 5 ml of test solution in a test tube • Add 3 drops of 0.25M lead acetate • *A white ppt. indicates a positive test for chlorides*
Nitrates (NO_3^{1-})	• Place a few crystals of $FeSO_4$, in a spot plate, and add 2-3 drops of test solution. • Add a few drops of concentrated H_2SO_4 to the edge of the solution. • *A brown color forming near the crystals indicates a positive test for nitrates*	• Place approximately 1 ml of test solution in a test tube • Add 3 drops of diphenylamine reagent • *A blue color indicates a positive test for nitrates*
Phosphates (PO_4^{3-})	• Place approximately 5 ml of test solution in a test tube • Add 1-2 drops of 0.1M $AgNO_3$ • *A pale yellow ppt. indicates a positive test for phosphates*	• Place approximately 5 ml of test solution in a test tube • Add 1-2 drops of 0.25M BaCl • *A white, finely-clumped ppt. indicates a positive test for phosphates*

Table 21

A drop of reagent was added to a test tube half-filled with soil/water filtrate. Two controls were used for each test, deionized water and a 0.1M solution containing the anion being tested. Control solutions used were: sodium sulfate (Na_2SO_4); sodium chloride (NaCl); sodium nitrate ($NaNO_3$); and sodium phosphate (Na_2HPO_4). Every positive test was confirmed with another reagent, and every negative test was checked by adding a drop of control solution containing the anion to confirm the effectiveness of the reagent.

Reagents needed:
- 0.25M barium chloride, BaCl
- 0.25M lead acetate, $Pb(CH_3COO)_2$
- 0.1M silver nitrate, $AgNO_3$
- Iron-II-sulfate crystals, $FeSO_4$
- Concentrated sulfuric acid, H_2SO_4
- Diphenylamine reagent (solution in H_2SO_4)

MUNSELL SOIL COLORS

Soil	Dry Color		Moist Color	
Mesa Verde Red	7.5YR 4/5	brown/strong brown	7.5YR 3/4	dark brown
Mesa Verde Yellow	10YR 6.5/4	very pale brown/light yellowish brown	10YR 5/6	yellowish brown
Mesa Verde Blend	**7.5YR 5/4**	**brown**	**7.5YR 3.5/5**	**strong brown**
Hovenweep Pink	5YR 6/4	light yellowish brown	5YR 4/6	yellowish red
Hovenweep Red	5YR 4/6	yellowish red	5YR 3/4	dark reddish brown
Chimney Rock Middle	10YR 5/3.5	brown/yellowish brown	10YR 3/3	dark brown
Chimney Rock Lower	10YR 5/4	yellowish brown	10YR 3/4	dark yellowish brown
Aztec Ruins Clay	10YR 5.5/3	pale brown/brown	10YR 4/3	brown/dark brown
Aztec Ruins Silt	10YR 5/3	brown	10YR 3/3	dark brown
Aztec Ruins Sand	10YR 5/3	brown	10YR 4/4	dark yellowish brown
Aztec Ruins Blend	**10YR 5.5/3**	**pale brown/brown**	**10YR 3/3**	**dark brown**
Chaco BLM Quarry	**10YR 4.5/3**	**brown/dark brown**	**10YR 4/3.5**	**dark brown/dark yellowish brown**
Chaco Chetro Ketl Field	10YR 4.5/3	brown/dark brown	10YR 4/3	brown/dark brown
Chaco South Gap	10YR 5/2.5	grayish brown/brown	10YR 3.5/3	dark brown
Chaco Chetro Ketl Prehistoric	10YR 5/4	yellowish brown	10YR 4/4	dark yellowish brown
Chaco Tsin Kletsin	10YR 6/3.5	pale brown/light yellowish brown	10YR 3.5/3	dark brown
New Mexico Alcalde Adobe	**10YR 6/3**	**pale brown**	**10YR 4/3**	**brown/dark brown**

Soils in bold type were tested as components in earthen mortars

Table 22

SOIL SHRINKAGE

Soil	Linear Shrinkage	Volumetric Shrinkage
Mesa Verde Red	5.6%	16.9%
Mesa Verde Yellow	2.4%	9.3%
Mesa Verde Blend	**4.5%**	**11.2%**
Hovenweep Pink	4.9%	14.8%
Hovenweep Red	3.5%	11.7%
Lower Chimney Rock	5.4%	16.6%
Middle Chimney Rock	3.6%	14.0%
Aztec Ruins Clay	5.6%	18.6%
Aztec Ruins Silt	4.3%	19.0%
Aztec Ruins Sand	0%	0%
Aztec Ruins Blend	**3.5%**	**9.2%**
Chaco Canyon South Gap	0.4%	5.1%
Chaco Canyon BLM Quarry	**4.9%**	**15.4%**
Chaco Canyon Tsin Kletsin	2.5%	7.0%
Chaco Canyon Chetro Ketl Field	12.3%	24.5%
Chaco Canyon Chetro Ketl Prehistoric	6.6%	18.6%
New Mexico Alcalde Adobe	**0.4%**	**3.3%**

Soils in bold type were tested as components of earthen mortars

Table 23

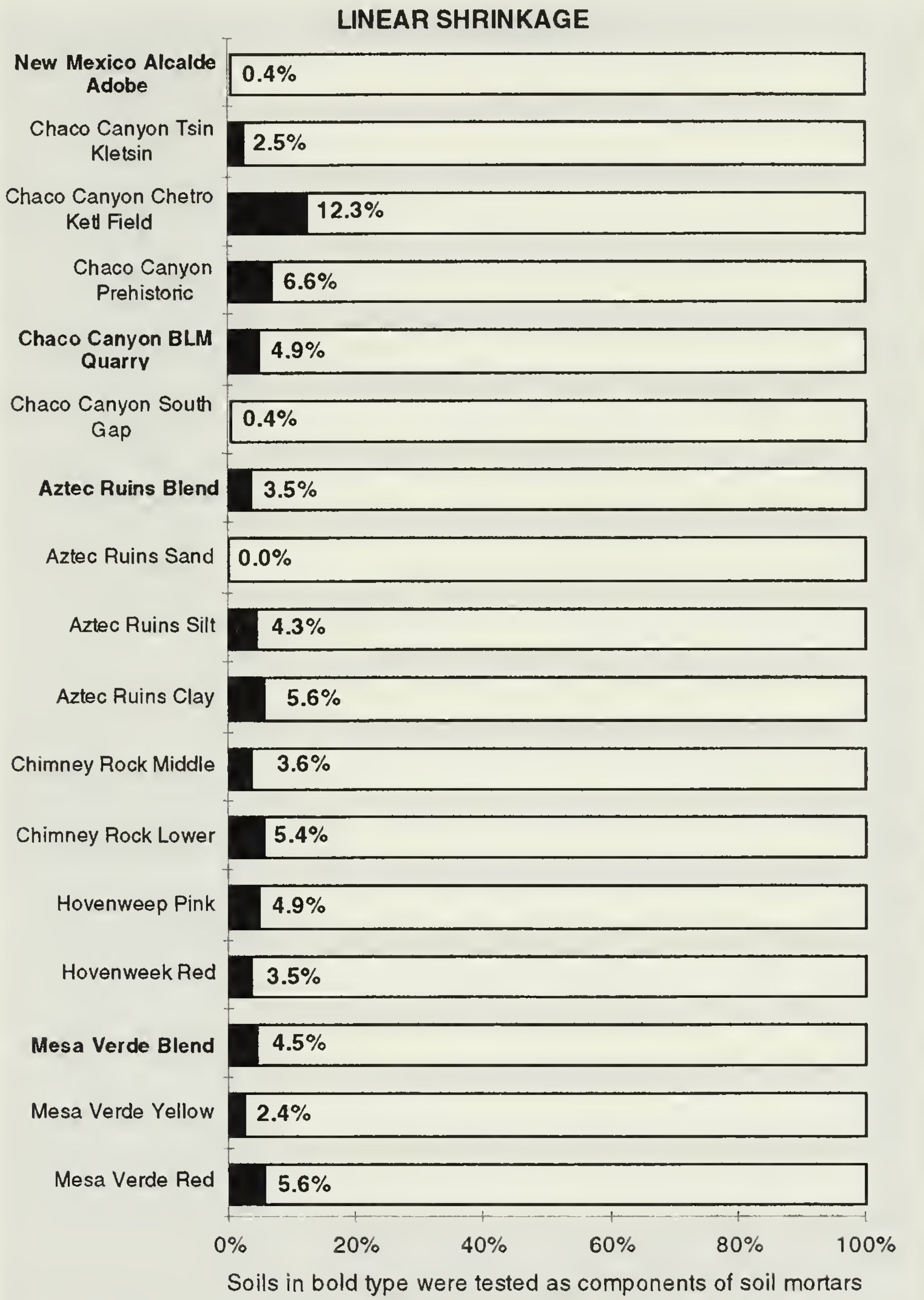

LINEAR SHRINKAGE
New Mexico Alcalde Adobe
0.4%
Chaco Canyon Tsin Kletsin
2.5%
Chaco Canyon Chetro Ketl Field
12.3%
Chaco Canyon Prehistoric
6.6%
Chaco Canyon BLM Quarry
4.9%
Chaco Canyon South Gap
0.4%
Aztec Ruins Blend
3.5%
Aztec Ruins Sand
0.0%
Aztec Ruins Silt
4.3%
Aztec Ruins Clay
5.6%
Chimney Rock Middle
3.6%
Chimney Rock Lower
5.4%
Hovenweep Pink
4.9%
Hovenweek Red
3.5%
Mesa Verde Blend
4.5%
Mesa Verde Yellow
2.4%
Mesa Verde Red
5.6%
0%
20%
40%
60%
80%
100%
Soils in bold type were tested as components of soil mortars

Figure 37

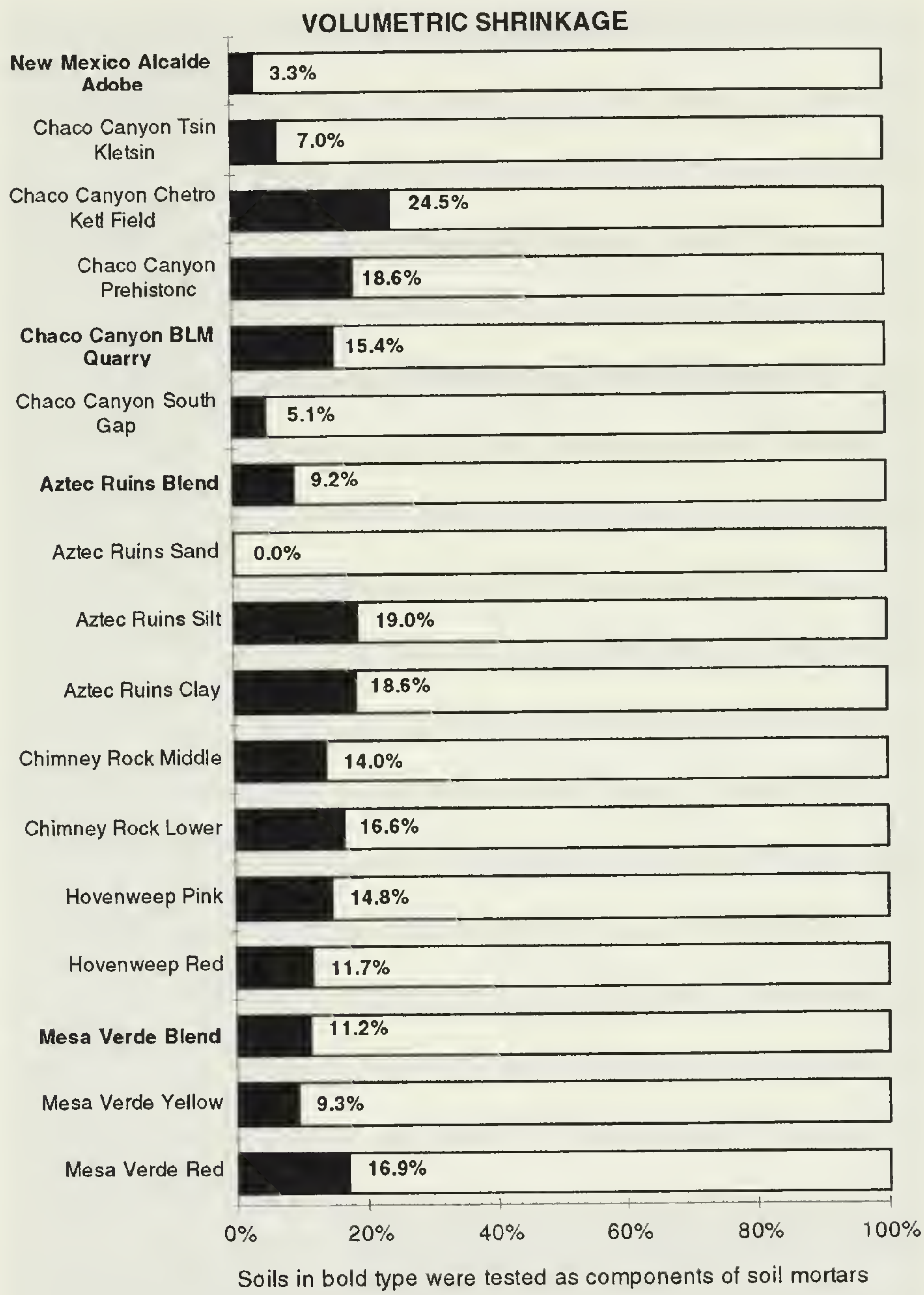

VOLUMETRIC SHRINKAGE
New Mexico Alcalde Adobe
3.3%
Chaco Canyon Tsin Kletsin
7.0%
Chaco Canyon Chetro Ketl Field
24.5%
Chaco Canyon Prehistoric
18.6%
Chaco Canyon BLM Quarry
15.4%
Chaco Canyon South Gap
5.1%
Aztec Ruins Blend
9.2%
Aztec Ruins Sand
0.0%
Aztec Ruins Silt
19.0%
Aztec Ruins Clay
18.6%
Chimney Rock Middle
14.0%
Chimney Rock Lower
16.6%
Hovenweep Pink
14.8%
Hovenweep Red
11.7%
Mesa Verde Blend
11.2%
Mesa Verde Yellow
9.3%
Mesa Verde Red
16.9%
0%
20%
40%
60%
80%
100%
Soils in bold type were tested as components of soil mortars

Figure 38

Appendix D

Earthen Mortar Test Data

Earthen Mortar Tests and Observations and Applicable Standards Used

(Details of the earthen mortar testing program are described in Chapter 4)

1. Test for durability when subjected to Wetting and Drying
   - *ASTM D559, Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures (modified)*
2. Test for durability when subjected to Freezing and Thawing
   - *ASTM D560, Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures (modified)*
3. Test for strength in bending, Modulus of Rupture
   - *ASTM D1635, Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading*
4. Test for Water Vapor Transmission
   - *ASTM E96, Standard Test Methods for Water Vapor Transmission of Materials (modified)*
5. Munsell color characterization (dry and moist, for each soil and Rhoplex combination)
   - *ASTM D1535, Standard Test Method for Specifying Color by the Munsell System*
6. Observation of earthen mortar micromorphology, using Scanning Electron Microscopy

EARTHEN MORTAR SAMPLE SCHEDULE

(Number Of Samples Molded For Physical Testing)

	SOIL Percent E-330																			
	Aztec Ruins Blend					Chaco Canyon BLM Quarry					Mesa Verde Blend					New Mexico Alcalde Adobe				
TEST	0	6	12.5	25	33	0	6	12.5	25	33	0	6	12.5	25	33	0	6	12.5	25	33
Freeze/Thaw **Cylinders:** **1.5" dia. x 1.5" h**	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Wetting/Drying **Cylinders:** **1.5" dia. x 1.5" h**	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Wetting/Drying (cold-dried) **Cylinders:** **1.5" dia. x 1.5" h**	2	2	2	2	2	-	-	-	-	-	2	2	2	2	2	2	2	2	2	2
Wetting/Drying (frozen, then air-dried at ambient conditions) **Cylinders:** **1.5" dia. x 1.5" h**	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-
Modulus of Rupture **Prisms:** **0.75"h x .075"d x 4.25" l**	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Modulus of Rupture (cold-dried) **Prisms:** **0.75"h x 0.75"d x 4.25" l**	-	-	-	-	-	4	4	4	4	4	4	4	4	4	4	-	-	-	-	-
Modulus of Rupture (frozen, then air-dried at ambient conditions) **Prisms:** **0.75"h x 0.75"d x 4.25" l**	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	-	-	-	4	-
WVT **Disks:** **0.75" h x 3.5" dia.**	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Table 24

MUNSELL EARTHEN MORTAR COLORS

Soil Mortar	E-330	Dry Color		Moist Color	
Mesa Verde Blend	0%	7.5YR 5/4	brown	7.5YR 4/5	dark brown/strong brown
	6%	7.5YR 5/5	brown	7.5YR 4/4	brown/dark brown
	12.5%	7.5YR 5/5	brown	7.5YR 4/4	brown/dark brown
Unamended Soil:	25%	7.5YR 4.5/5	brown/dark brown/strong brown	7.5YR 4/4	brown/dark brown
dry 7.5YR 5/4 moist 7.5YR 3.5/5	33%	7.5YR 4.5/5	brown/dark brown/strong brown	7.5YR 3.5/4	brown/dark brown
Aztec Ruins Blend	0%	10YR 5/3.5	brown/yellowish brown	10YR 3.5/3	dark brown
	6%	10YR 5/3	brown	10YR 3/3	dark brown
	12.5%	10YR 5/3.5	brown/yellowish brown	10YR 3.5/3	dark brown
Unamended Soil:	25%	10YR 4.5/3	brown/dark brown	10YR 3/3	dark brown
dry 10YR 5.5/3 moist 10YR 3/3	33%	10YR 5/3.5	brown/yellowish brown	10YR 3.5/3	dark brown
Chaco BLM Quarry	0%	10YR 5/3	brown	10YR 3.5/2.5	dark brown/dark grayish brown
	6%	10YR 5/3	brown	10YR 3.5/2.5	dark brown/dark grayish brown
	12.5%	10YR 5/3	brown	10YR 3.5/2.5	dark brown/dark grayish brown
Unamended Soil:	25%	10YR 5/3	brown	10YR 3.5/2.5	dark brown/dark grayish brown
dry 10YR 4.5/3 moist 7.5YR 4/3.5	33%	10YR 5/3	brown	10YR 3.5/2.5	dark brown/dark grayish brown
New Mexico Alcalde Adobe	0%	10YR 5.5/3	brown/pale brown	10YR 3.5/3	dark brown
	6%	10YR 5.5/3	brown/pale brown	10YR 3.5/3	dark brown
Unamended Soil:	12.5%	10YR 5.5/3	brown/pale brown	10YR 3.5/3	dark brown
dry 10YR 6/3	25%	10YR 5.5/3	brown/pale brown	10YR 4.5/3	brown/dark brown
moist 10YR 4/3	33%	10YR 5.5/3	brown/pale brown	10YR 4.5/3	brown/dark brown

Table 25

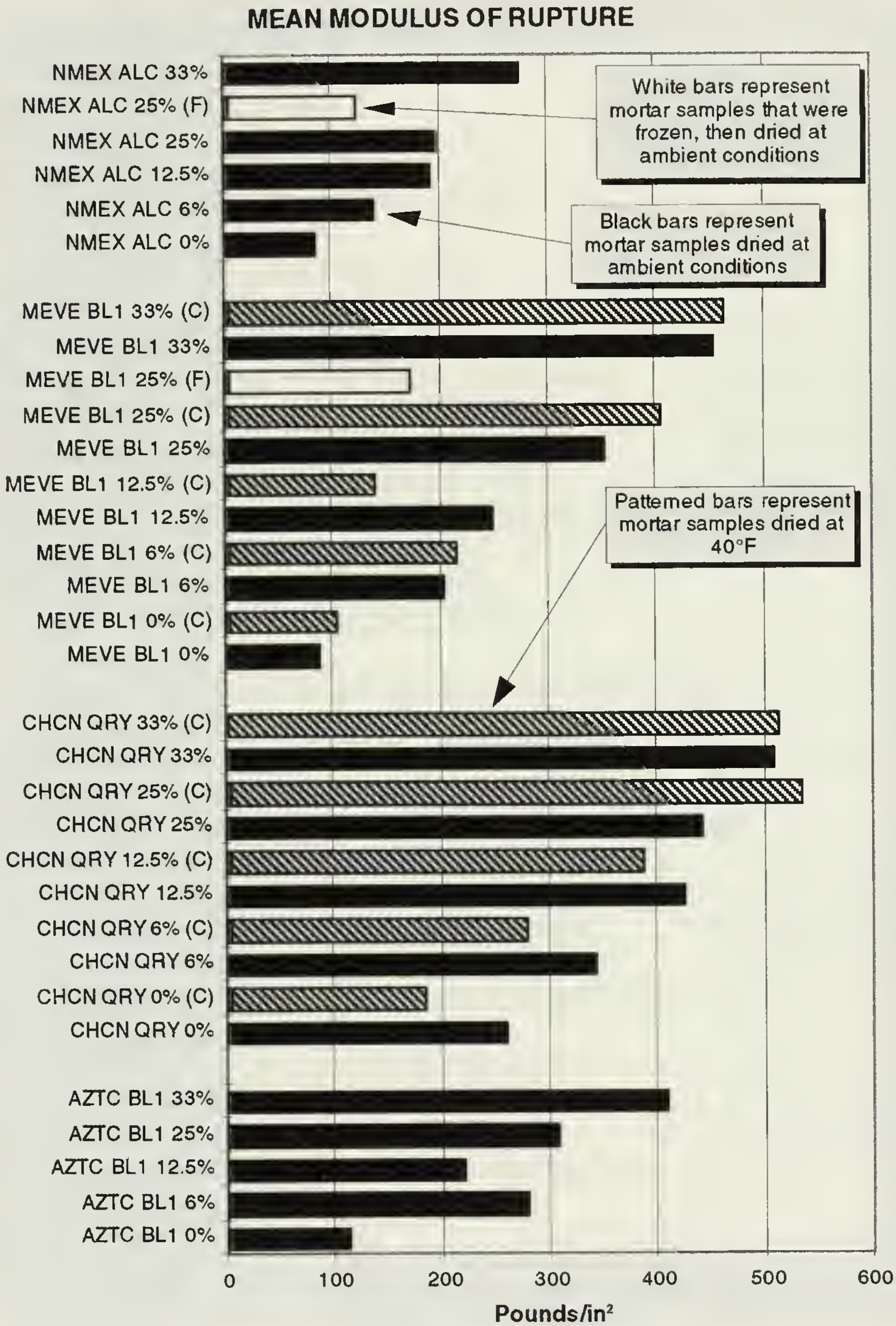


Figure 39. Modulus of Rupture summary data, n ≤4.

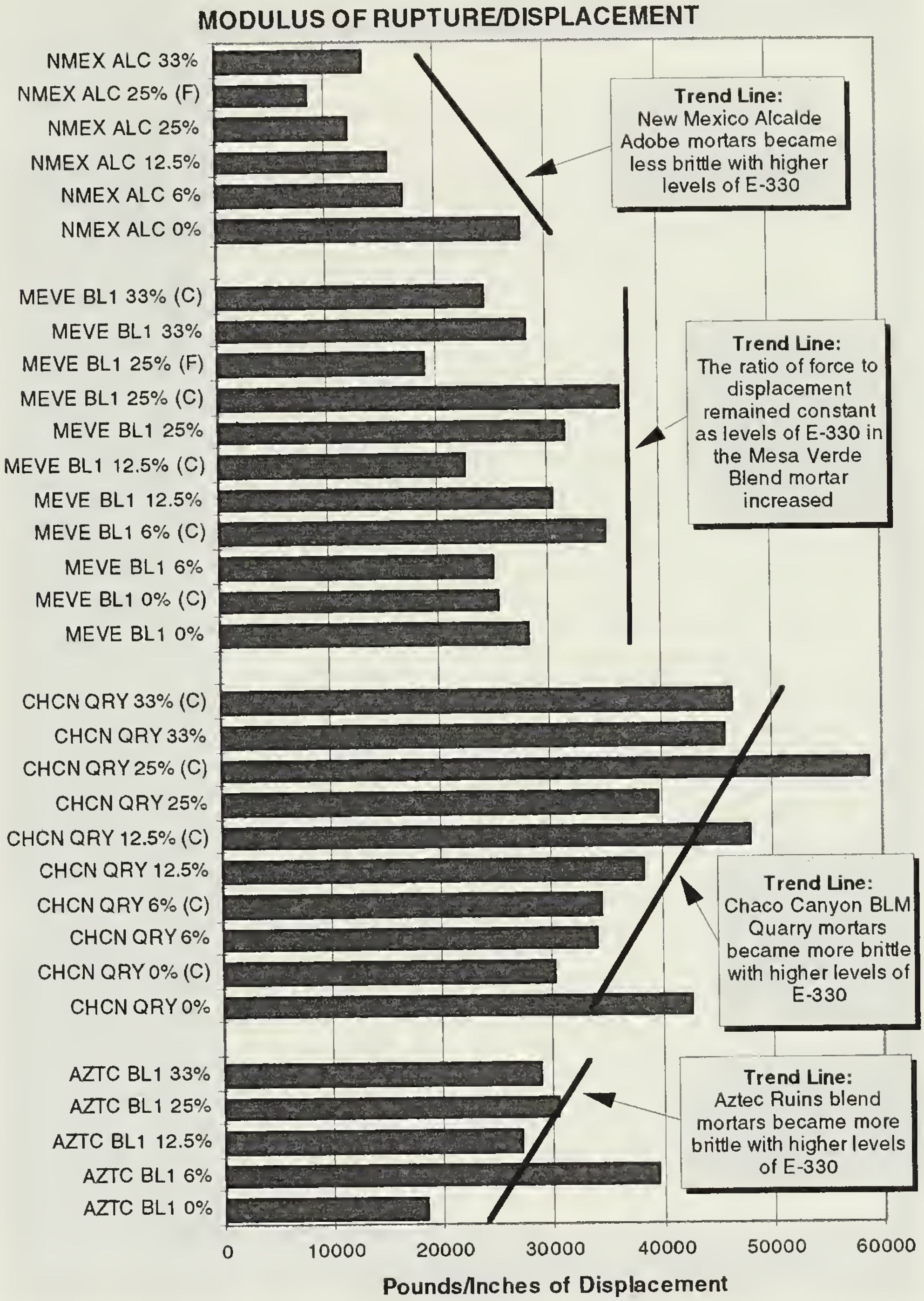


Figure 40. Ratio of the mean Modulus of Rupture and mean displacement, n ≤4.

MODULUS OF RUPTURE AND DISPLACEMENT DATA

Soil Type and E-330 Concentration*	n	Mean Modulus of Rupture (psi)	MoR Range	Standard Deviation, Modulus of Rupture	Mean Displacement (in.)	Displacement Range (in.)	Standard Deviation, Displacement
AZTC BL1 0%	4	110	131-144	7.7	0.0060	0.005-0.007	0.001
AZTC BL1 6%	4	275	261-288	12.2	0.0070	0.005-0.009	0.002
AZTC BL1 12.5%	4	215	96-277	84.9	0.0080	0.002-0.012	0.004
AZTC BL1 25%	4	303	277-331	21.9	0.0100	0.009-0.010	0.001
AZTC BL1 33%	4	404	363-411	38.3	0.0140	0.012-0.015	0.002
CHCN QRY 0%	4	255	224-280	25.1	0.0060	0.005-0.009	0.002
CHCN QRY 0% (C)	4	180	136-221	42.3	0.0060	0.003-0.009	0.003
CHCN QRY 6%	3	340	299-368	36.8	0.0100	0.0100	0
CHCN QRY 6% (C)	4	275	189-368	73.6	0.0080	0.004-0.010	0.003
CHCN QRY 12.5%	4	421	405-437	18.5	0.0110	0.009-0.013	0.002
CHCN QRY 12.5% (C)	4	384	368-400	13.8	0.0080	0.006-0.01	0.002
CHCN QRY 25%	4	437	245-541	130.8	0.0110	0.007-0.014	0.003
CHCN QRY 25% (C)	4	529	504-552	22.5	0.0090	0.008-0.012	0.002
CHCN QRY 33%	4	504	443-571	52.5	0.0110	0.009-0.012	0.001
CHCN QRY 33% (C)	3	510	437-587	74.7	0.0110	0.009-0.012	0.002
MEVE BL1 0%	3	84	77-93	8.6	0.0030	0.002-0.004	0.001
MEVE BL1 0% (C)	4	101	85-115	12	0.0040	0.003-0.004	0.001
MEVE BL1 6%	4	199	181-216	14.2	0.0080	0.006-0.009	0.001
MEVE BL1 6% (C)	4	211	176-232	25.3	0.0060	0.006-0.007	0
MEVE BL1 12.5%	4	243	165-320	89.3	0.0080	0.007-0.010	0.002
MEVE BL1 12.5% (C)	4	135	106-149	19.2	0.0060	0.003-0.008	0.002
MEVE BL1 25%	4	347	331-357	13.1	0.0110	0.008-0.012	0.002
MEVE BL1 25% (C)	4	401	357-512	74.1	0.0110	0.009-0.013	0.002
MEVE BL1 25% (F)	4	169	128-261	61.9	0.0090	0.007-0.010	0.002
MEVE BL1 33%	4	449	363-507	62.6	0.0160	0.015-0.019	0.002
MEVE BL1 33% (C)	4	459	411-533	52.4	0.0190	0.014-0.023	0.004
NMEX ALC 0%	2	83	77-88	n/a	0.0030	0.002-0.004	n/a
NMEX ALC 6%	4	135	128-139	5.1	0.0080	0.007-0.010	0.001
NMEX ALC 12.5%	4	187	168-197	12.9	0.0120	0.011-0.012	0.001
NMEX ALC 25%	4	191	171-221	23.7	0.0160	0.015-0.016	0.001
NMEX ALC 25% (F)	4	118	91-139	20.2	0.0140	0.011-0.017	0.003
NMEX ALC 33%	4	269	224-309	41.2	0.0200	0.016-0.026	0.004

*(C) = cold-dried, at approximately 40°F
(F) = frozen, and air-dried at ambient laboratory conditions

Table 26

RATIO: MODULUS OF RUPTURE/DISPLACEMENT

Soil Type and E-330 Concentration*	Mean Modulus of Rupture (psi)	Mean Deviation	Ratio: M/R: Displacement (pounds/inch)	n	Range
AZTC BL1 0%	110	0.0060	18333	4	0.005-0.007
AZTC BL1 6%	275	0.0070	39286	4	0.005-0.009
AZTC BL1 12.5%	215	0.0080	26875	4	0.002-0.012
AZTC BL1 25%	303	0.0100	30300	4	0.009-0.010
AZTC BL1 33%	404	0.0140	28857	4	0.012-0.015
CHCN QRY 0%	255	0.0060	42500	4	0.005-0.009
CHCN QRY 0% (C)	180	0.0060	30000	4	0.003-0.009
CHCN QRY 6%	340	0.0100	34000	3	0.0100
CHCN QRY 6% (C)	275	0.0080	34375	4	0.004-0.010
CHCN QRY 12.5%	421	0.0110	38273	4	0.009-0.013
CHCN QRY 12.5% (C)	384	0.0080	48000	4	0.006-0.01
CHCN QRY 25%	437	0.0110	39727	4	0.007-0.014
CHCN QRY 25% (C)	529	0.0090	58778	4	0.008-0.012
CHCN QRY 33%	504	0.0110	45818	4	0.009-0.012
CHCN QRY 33% (C)	510	0.0110	46364	3	0.009-0.012
MEVE BL1 0%	84	0.0030	28000	4	0.002-0.004
MEVE BL1 0% (C)	101	0.0040	25250	4	0.003-0.004
MEVE BL1 6%	199	0.0080	24875	4	0.006-0.009
MEVE BL1 6% (C)	211	0.0060	35167	4	0.006-0.007
MEVE BL1 12.5%	243	0.0080	30375	4	0.007-0.010
MEVE BL1 12.5% (C)	135	0.0060	22500	4	0.003-0.008
MEVE BL1 25%	347	0.0110	31545	4	0.008-0.012
MEVE BL1 25% (C)	401	0.0110	36455	4	0.009-0.013
MEVE BL1 25% (F)	169	0.0090	18778	4	0.007-0.010
MEVE BL1 33%	449	0.0160	28063	4	0.015-0.019
MEVE BL1 33% (C)	459	0.0190	24158	4	0.014-0.023
NMEX ALC 0%	83	0.0030	27667	2	0.002-0.004
NMEX ALC 6%	135	0.0080	16875	4	0.007-0.010
NMEX ALC 12.5%	187	0.0120	15583	4	0.011-0.012
NMEX ALC 25%	191	0.0160	11938	4	0.015-0.016
NMEX ALC 25% (F)	118	0.0140	8429	4	0.011-0.017
NMEX ALC 33%	269	0.0200	13450	4	0.016-0.026

*(C) = cold-dried, at approximately 40°F
(F) = frozen, and air-dried at ambient laboratory conditions

Table 27

NOTE. THESE RATE VALUES ARE INCORRECT SEE TA437.H37 FOR THE CORRECT VALUES HOWEVER THE RELATIONSHIP OF WVT VALUES AMONG AMENDED SOIL GROUPS IS CORRECT.

WATER VAPOR TRANSMISSION

Earthen mortar	Water Vapor Transmission Rate g/h·m²	Permeance g/Pa·s·m²	Permeability g/Pa·s·m
Aztec Ruins Blend 0%	1.00×10^{-4}	1.56×10^{-13}	2.97×10^{-15}
Aztec Ruins Blend 6%	9.07×10^{-5}	1.44×10^{-13}	2.73×10^{-15}
Aztec Ruins Blend 12.5%	9.25×10^{-5}	1.44×10^{-13}	2.74×10^{-15}
Aztec Ruins Blend 24%	8.39×10^{-5}	1.33×10^{-13}	2.07×10^{-15}
Aztec Ruins Blend 33%	7.00×10^{-5}	1.09×10^{-13}	3.58×10^{-15}
Chaco Canyon BLM Quarry 0%	1.21×10^{-4}	1.88×10^{-13}	3.58×10^{-15}
Chaco Canyon BLM Quarry 6%	1.12×10^{-4}	1.77×10^{-13}	3.36×10^{-15}
Chaco Canyon BLM Quarry 12.5%	1.01×10^{-4}	1.57×10^{-13}	2.99×10^{-15}
Chaco Canyon BLM Quarry 25%	9.48×10^{-5}	1.50×10^{-13}	2.85×10^{-15}
Chaco Canyon BLM Quarry 33%	8.12×10^{-5}	1.26×10^{-13}	2.40×10^{-15}
Mesa Verde Blend 0%	1.38×10^{-4}	2.15×10^{-13}	4.09×10^{-15}
Mesa Verde Blend 6%	1.24×10^{-4}	1.98×10^{-13}	3.73×10^{-15}
Mesa Verde Blend 12.5%	1.13×10^{-4}	1.78×10^{-13}	3.34×10^{-15}
Mesa Verde Blend 25%	1.01×10^{-4}	1.60×10^{-13}	3.04×10^{-15}
Mesa Verde Blend 33%	8.67×10^{-5}	1.35×10^{-13}	2.56×10^{-15}
New Mexico Alcalde Adobe 0%	1.27×10^{-4}	1.98×10^{-13}	3.76×10^{-15}
New Mexico Alcalde Adobe 6%	1.31×10^{-4}	2.07×10^{-13}	3.93×10^{-15}
New Mexico Alcalde Adobe 12.5%	1.17×10^{-4}	1.82×10^{-13}	3.46×10^{-15}
New Mexico Alcalde Adobe 25%	1.08×10^{-4}	1.71×10^{-13}	3.25×10^{-15}
New Mexico Alcalde Adobe 33%	8.74×10^{-5}	1.36×10^{-13}	2.58×10^{-15}

Table 28

ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials* defines the following terms: 1) *water vapor transmission rate,* the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface; 2) *water vapor permeability,* the time rate of water vapor transmission through a unit area of a flat material of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions; and 3) *water vapor permeance,* the time rate of water vapor transmission through unit area of flat material or construction induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions.

COMPARATIVE WVT DATA
FOUR SOUTHWESTERN SOILS AMENDED WITH E-330

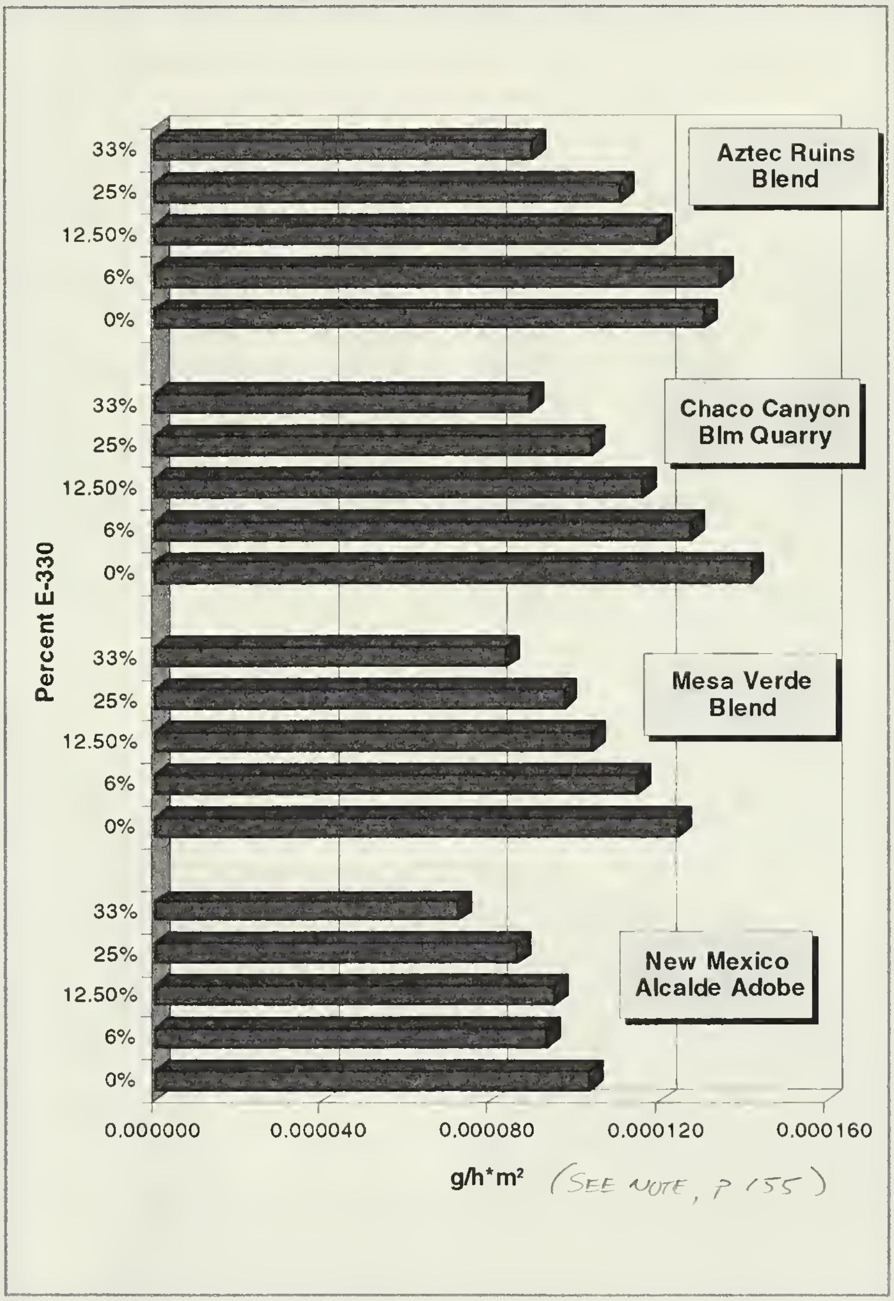


Figure 41

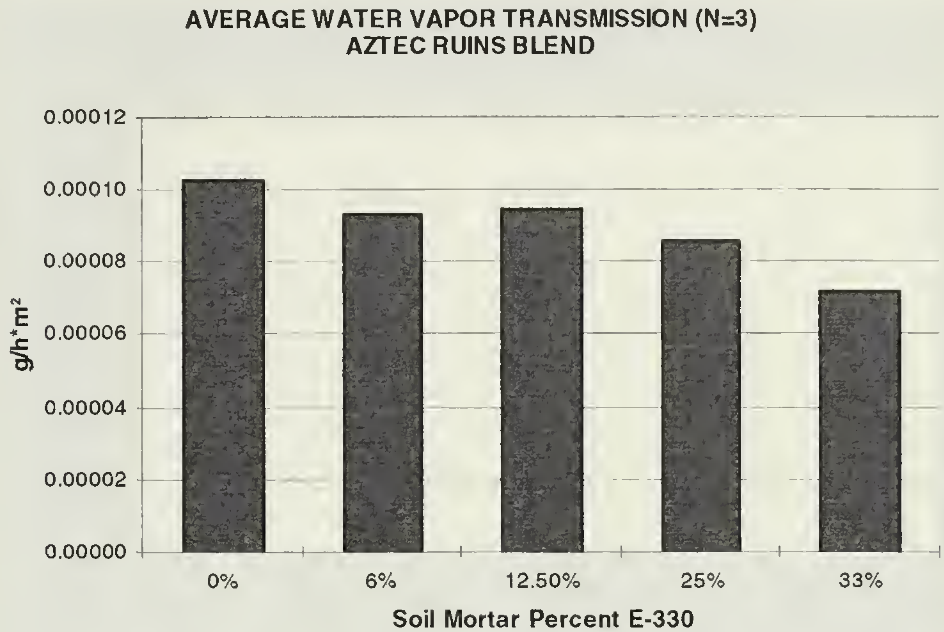


Figure 42

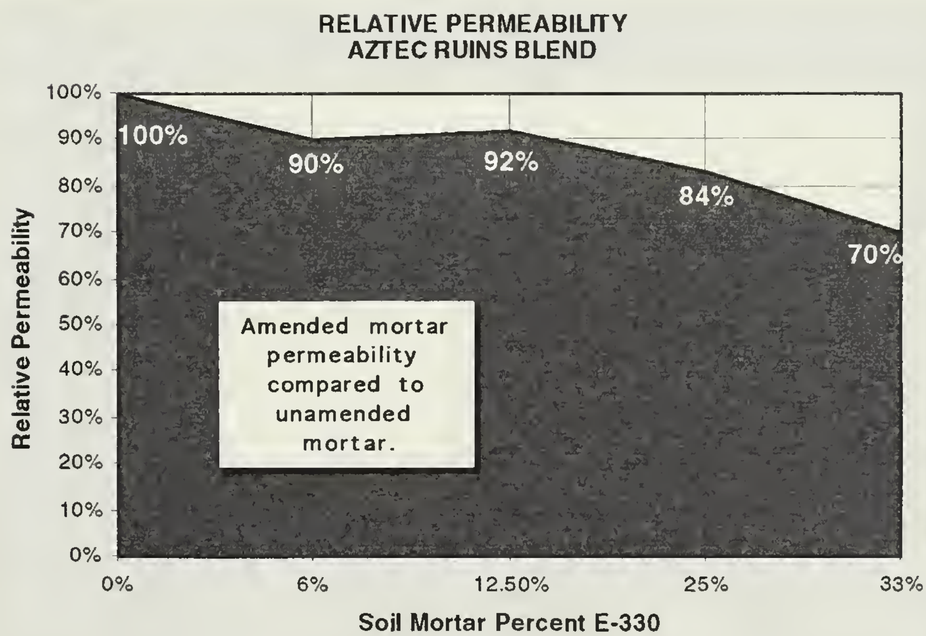


Figure 43

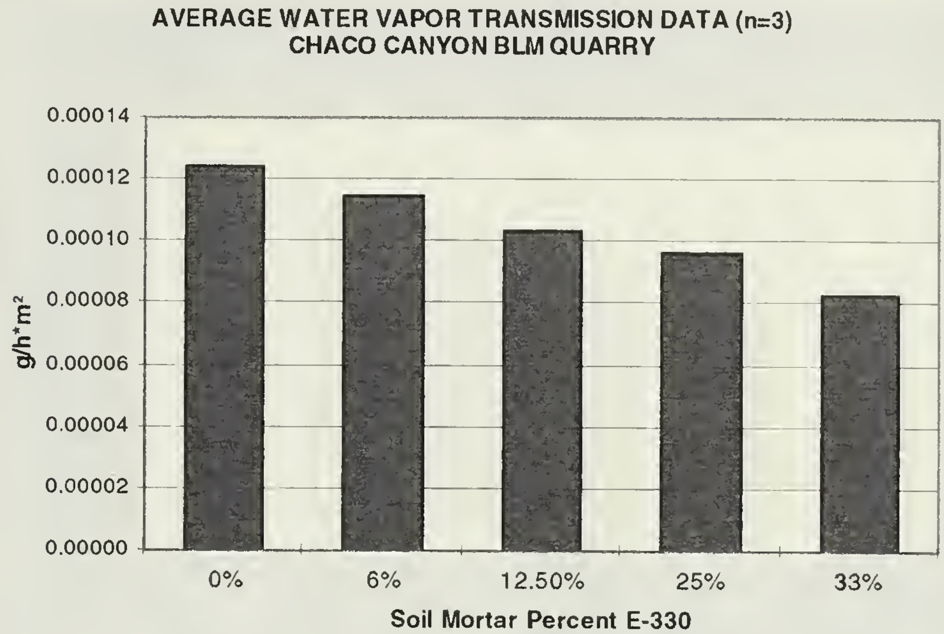


Figure 44

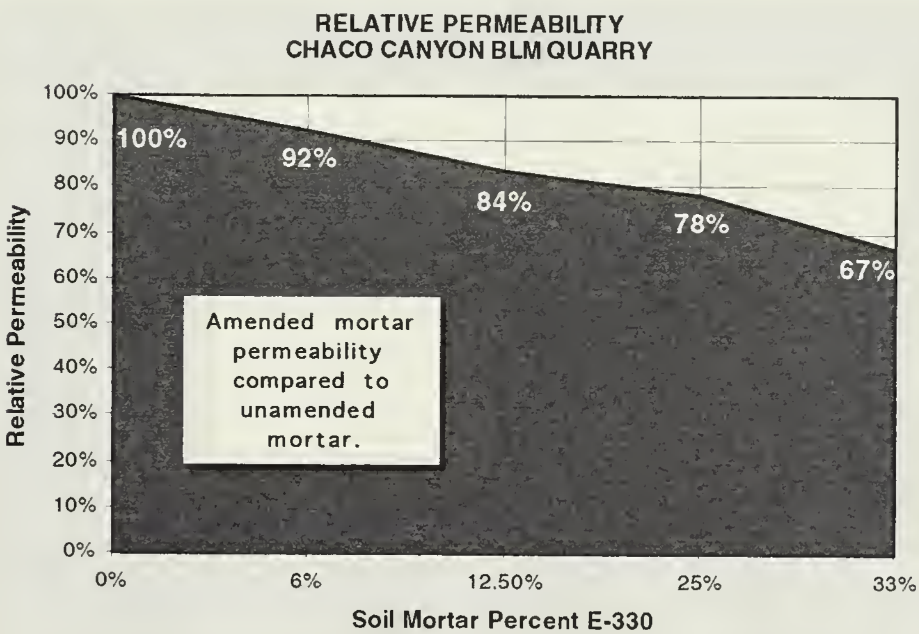


Figure 45

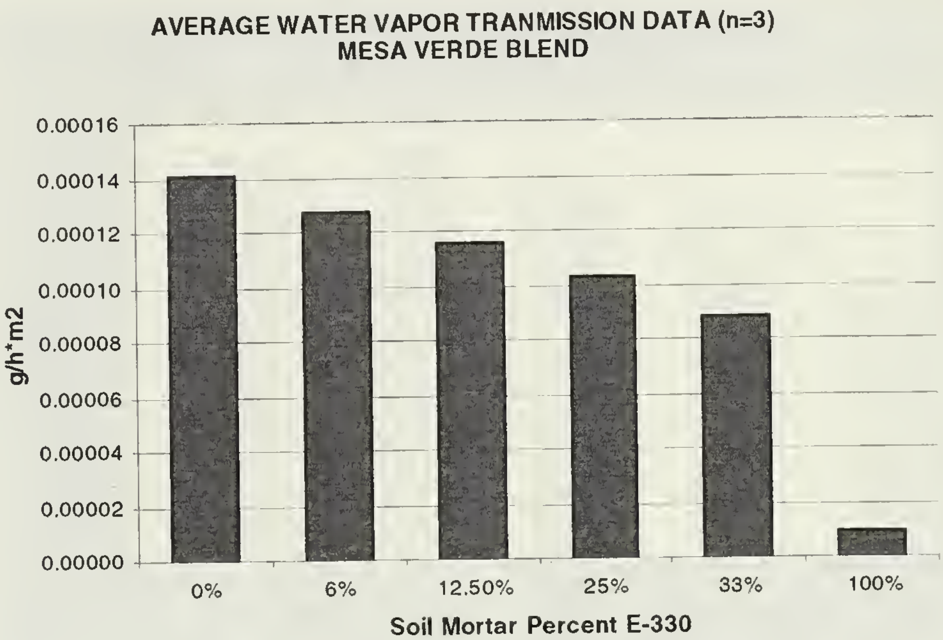


Figure 46

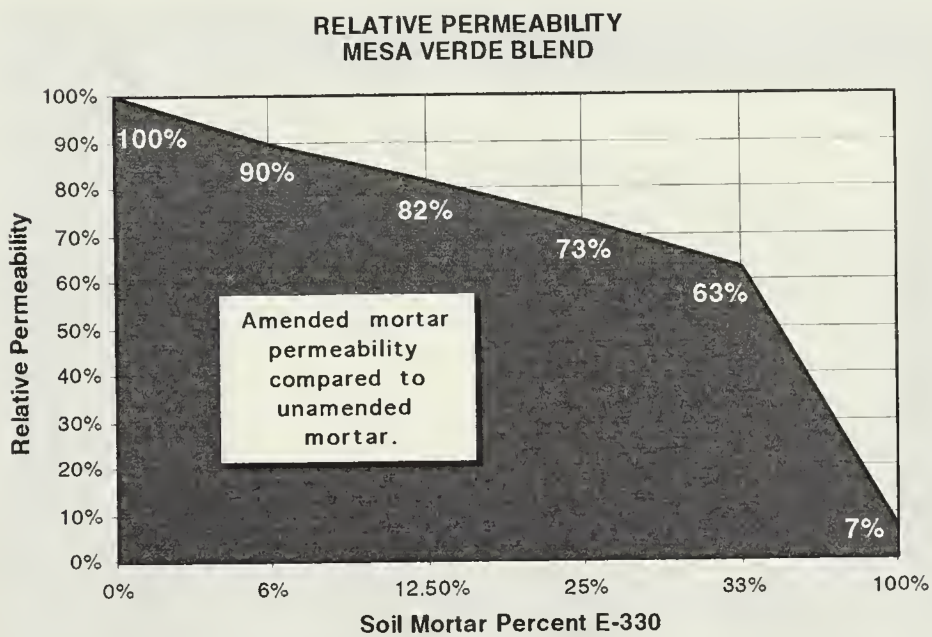


Figure 47

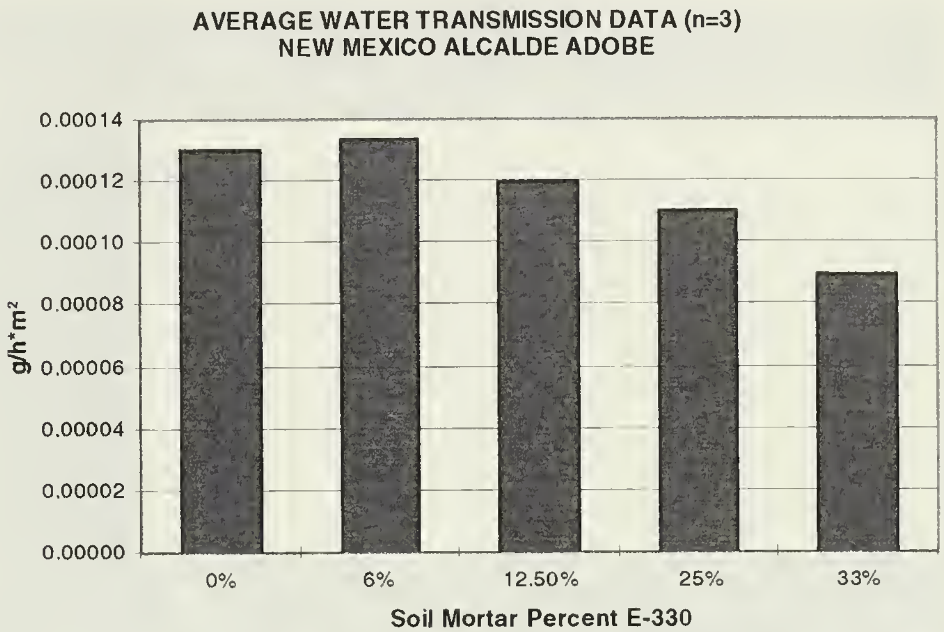


Figure 48

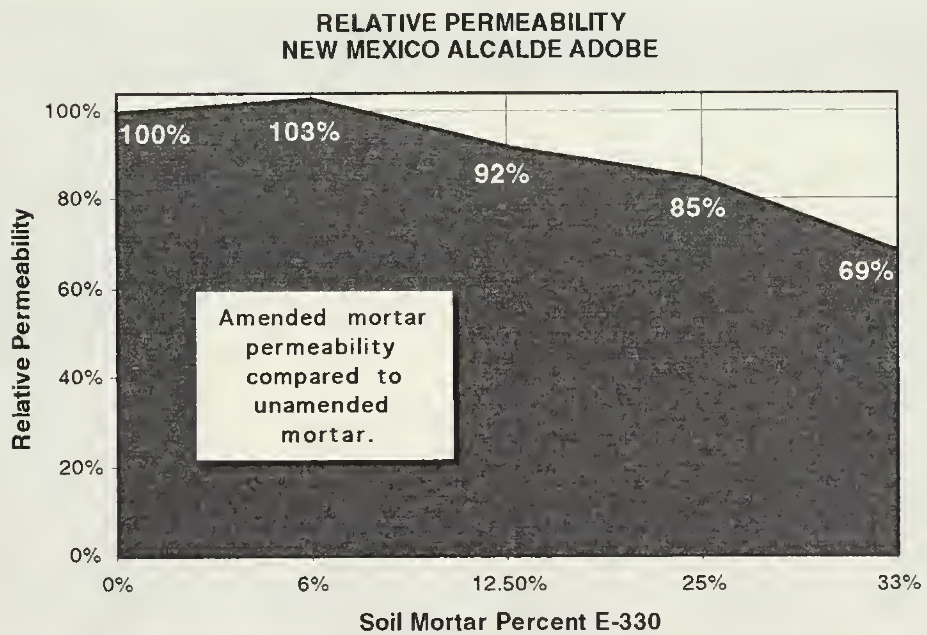


Figure 49

WETTING/DRYING DATA AND OBSERVATIONS

Earthen mortar*	Initial Wt. (g)	Final Wt. (g)	Chg. in Wt.	% Change	Cycles	Notes
AZTC 0 #1	88.41	0.00	-88.41	-100.0%	0	Disintegrated on first immersion
AZTC 0 #2	88.49	0.00	-88.49	-100.0%	0	Disintegrated on first immersion
AZTC 0 (C) #1	87.92	0.00	-87.92	-100.0%	0	Disintegrated on first immersion
AZTC 0 (C) #2	87.77	0.00	-87.77	-100.0%	0	Disintegrated on first immersion
AZTC 6 #1	84.35	83.93	-0.42	-0.5%	10	Slight, fine cracking
AZTC 6 #2	84.99	84.43	-0.56	-0.7%	10	Slight, fine cracking
AZTC 6 (C) #1	83.58	83.60	0.02	0.0%	10	
AZTC 6 (C) #2	85.05	84.61	-0.44	-0.5%	10	
AZTC 12.5 #1	81.92	81.94	0.02	0.0%	7	Slight, fine cracking on sides
AZTC 12.5 #2	83.01	82.97	-0.04	0.0%	7	Slight, fine cracking on sides
AZTC 12.5 (C) #1	84.30	84.33	0.03	0.0%	7	Slight, fine cracking on sides
AZTC 12.5 (C) #2	84.42	84.48	0.06	0.1%	7	Slight, fine cracking on sides
AZTC 25 #1	81.28	81.34	0.06	0.1%	7	Slight, fine cracking on sides
AZTC 25 #2	82.00	82.00	0.00	0.0%	7	Slight, fine cracking on sides
AZTC 25 (C) #1	81.44	81.53	0.09	0.1%	7	Slight, fine cracking on sides
AZTC 25 (C) #2	82.03	82.08	0.05	0.1%	7	
AZTC 33 #1	81.19	81.32	0.13	0.2%	7	
AZTC 33 #2	80.14	80.16	0.02	0.0%	7	
AZTC 33 (C) #1	77.68	77.68	0.00	0.0%	7	
AZTC 33 (C) #2	78.87	78.80	-0.07	-0.1%	7	
CHCN 0 #1	72.06	0.00	-72.06	-100.0%	0	Disintegrated on first immersion
CHCN 0 #2	73.35	0.00	-73.35	-100.0%	0	Disintegrated on first immersion
CHCN 6 #1	75.16	31.78	-43.38	-57.7%	7	
CHCN 6 #2	75.60	43.59	-32.01	-42.3%	7	
CHCN 12.5 # 1	73.01	57.12	-15.89	-21.8%	17	Large flakes, broad cracking
CHCN 12.5 #2	71.61	71.57	-0.04	-0.1%	10	Broad map cracking
CHCN 25 #1	70.76	70.74	-0.02	0.0%	7	Increasing gross cracking on sides
CHCN 25 #2	70.94	71.00	0.06	0.1%	7	Increasing gross cracking on sides
CHCN 33 #1	71.17	71.08	-0.09	-0.1%	7	Some cracking on sides
CHCN 33 #2	70.07	70.17	0.10	0.1%	7	Some cracking on sides

* (C) = cold-dried, at approximately 40°F

Table 29

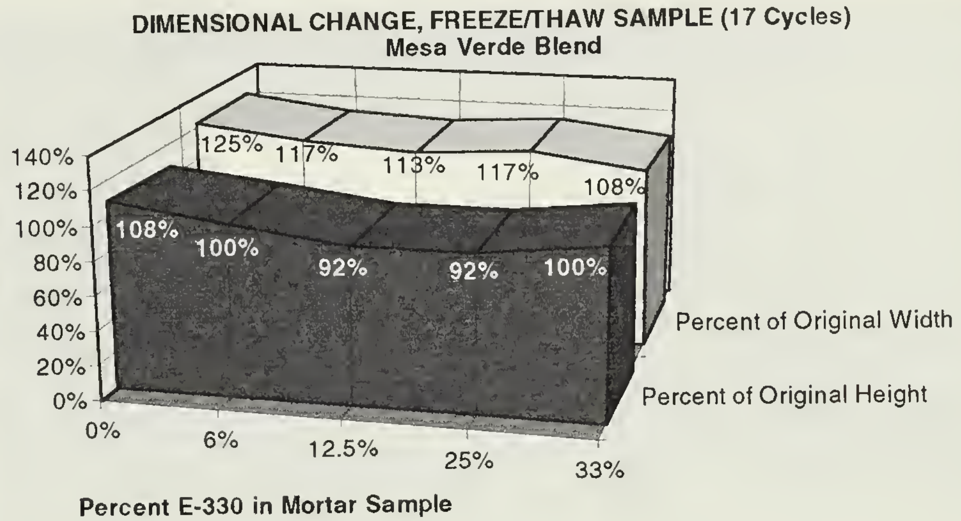
(continued on next page)

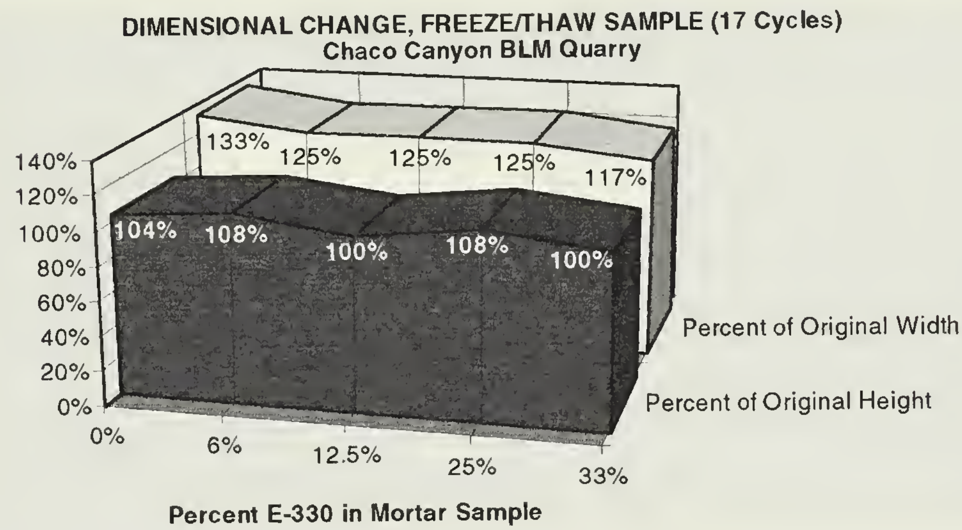
WETTING/DRYING DATA AND OBSERVATIONS

Earthen mortar*	Initial Wt. (g)	Final Wt. (g)	Chg. in Wt.	% Change	Cycles	Notes
MEVE 0 #1	77.01	0.00	-77.01	-100.0%	0	Disintegrated on first immersion
MEVE 0 #2	77.36	0.00	-77.36	-100.0%	0	Disintegrated on first immersion
MEVE 0 (c) #1	75.11	0.00	-75.11	-100.0%	0	Disintegrated on first immersion
MEVE 0 (c) #2	74.99	0.00	-74.99	-100.0%	0	Disintegrated on first immersion
MEVE 6 #1	76.72	75.54	-1.18	-1.5%	10	Fine map cracking, contour scaling
MEVE 6 #2	76.60	69.86	-6.74	-8.8%	17	Fine map cracking, contour scaling, fine flaking
MEVE 6 #3	78.00	36.84	-41.16	-52.8%	6	Surface deteriorated in fine flakes
MEVE 6 #4	76.30	41.60	-34.70	-45.5%	6	Surface deteriorated in fine flakes
MEVE 6 (c) #1	76.96	64.31	-12.65	-16.4%	10	Fine cracking, disintegrating. in layers, basal erosion
MEVE 6 (c) #2	74.18	71.86	-2.32	-3.1%	10	Fine cracking, disintegrating. in layers, basal erosion
MEVE 12.5 #1	76.01	74.72	-1.29	-1.7%	17	Flaking, fine cracks, contour scaling
MEVE 12.5 #2	72.70	72.68	-0.02	0.0%	10	Fewer cracks than MEVE 12.5 #1
MEVE 12.5 (C) #1	74.03	73.92	-0.11	-0.1%	10	Few fine cracks on sides
MEVE 12.5 (C) #2	73.97	73.95	-0.02	0.0%	10	
MEVE 25 #1	71.35	70.59	-0.76	-1.1%	17	Some fine cracks, flaking loss at bottom
MEVE 25 #2	70.65	70.53	-0.12	-0.2%	10	Fine cracks appearing on bottom
MEVE 25 (C) #1	71.10	70.93	-0.17	-0.2%	10	
MEVE 25 (C) #2	71.45	71.33	-0.12	-0.2%	10	
MEVE 25 (F) #1	70.70	70.47	-0.23	-0.3%	10	Fine flakes, vertical. parallel cracks (unique to frozen samples)
MEVE 25 (F) #2	71.80	71.66	-0.14	-0.2%	10	Fine flakes, vertical. parallel cracks (unique to frozen samples)
MEVE 33 #1	71.16	70.83	-0.33	-0.5%	17	Some fine cracks appeared, small flakes on bottom
MEVE 33 #2	70.47	70.30	-0.17	-0.2%	10	
MEVE 33 (C) #1	70.04	69.83	-0.21	-0.3%	10	
MEVE 33 (C) #2	70.77	70.58	-0.19	-0.3%	10	
NMEX 0 #1	84.85	0.00	-84.85	-100.0%	0	Disintegrated on first immersion
NMEX 0 (C) #1	82.18	0.00	-82.18	-100.0%	0	Disintegrated on first immersion
NMEX 0 (C) #2	83.54	0.00	-83.54	-100.0%	0	Disintegrated on first immersion
NMEX 0 (C) #3	83.29	0.00	-83.29	-100.0%	0	Disintegrated on first immersion
NMEX 6 #1	79.50	79.38	-0.12	-0.2%	10	(no cracking on any NMEX samples)
NMEX 6 #2	80.08	80.03	-0.05	-0.1%	10	
NMEX 6 (C) #1	81.45	81.26	-0.19	-0.2%	10	
NMEX 6 (C) #2	75.18	74.25	-0.93	-1.2%	7	Slight granular loss
NMEX 12.5 #1	79.55	79.43	-0.12	-0.2%	7	
NMEX 12.5 #1 (C)	79.10	79.00	-0.10	-0.1%	7	
NMEX 25 #1	78.34	78.25	-0.09	-0.1%	7	
NMEX 25 (C) #1	78.95	78.91	-0.04	-0.1%	7	
NMEX 33 #2	76.77	76.70	-0.07	-0.1%	7	
NMEX 33 (C) #1	77.77	77.63	-0.14	-0.2%	7	

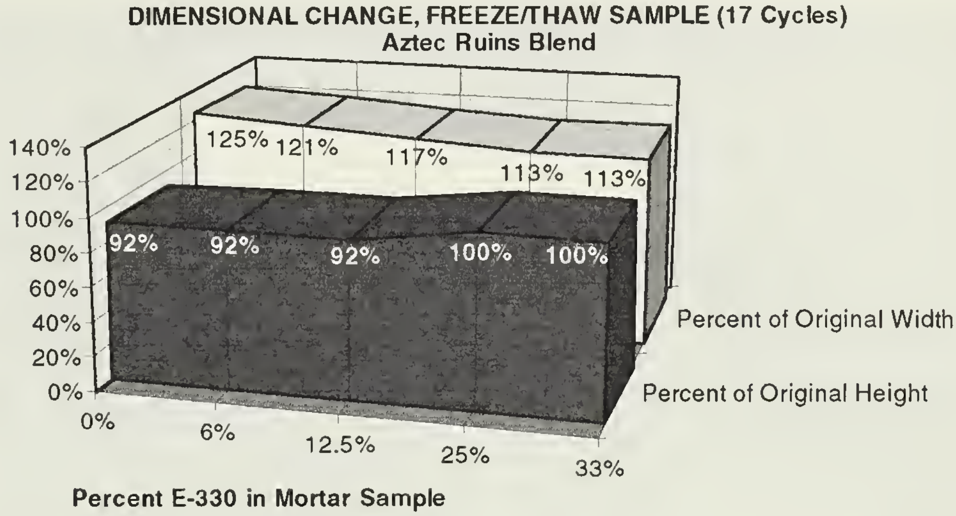
*(C) = cold-dried, at approximately 40°F
(F) = frozen, and air-dried at ambient laboratory conditions

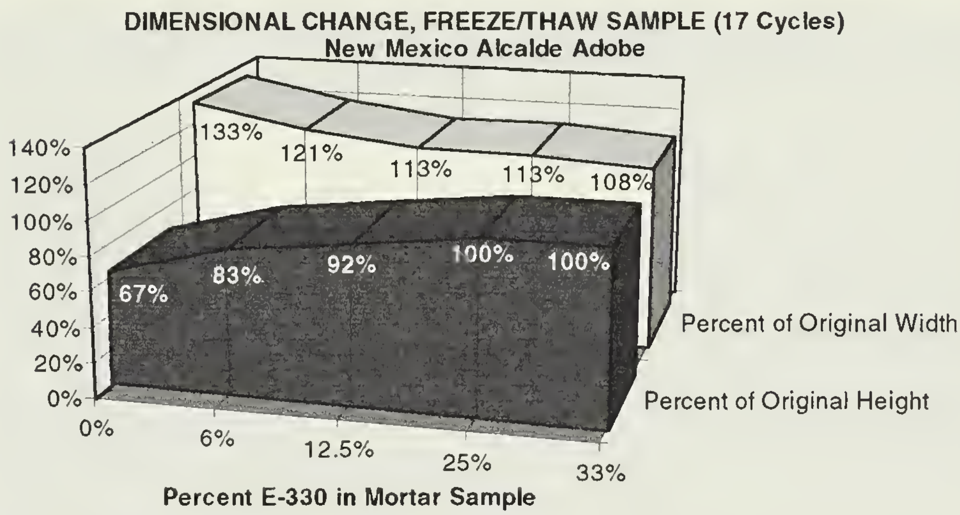
Table 29
(continued from previous page)





Figures 50 and 51. These graphs, and the two on the following page, demonstrate one difference between the mortar soils in the freeze/thaw test. The two soils with the highest clay and silt content, Mesa Verde Blend and Chaco Canyon BLM Quarry, swelled more in constant contact with water. They maintained their original height, or nearly so, while swelling to up to one-fourth or one-third in diameter. The amount of E-330 in the mortar formula had only a slight effect in constricting the dimensional changes of these two soils. Compare these results with those on the following page.





Figures 52 and 53. The two soils with the highest sand content, Aztec Ruins Blend and New Mexico Alcalde Adobe, slumped when saturated, expanding in diameter but shrinking in height, unlike the higher clay soils on the previous page. Sandy soils, such as the New Mexico adobe soil, contain little natural adhesive, clay, and are easily decayed by water. Increasing amounts of E-330 in the mortar formula had a pronounced effect in constricting the dimensional changes of these two soils. At 33%, the soils were close to their original dimensions after 17 cycles of freezing and thawing. And the effect was consistent; more E-330, less dimensional change.

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