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An Evaluation of Shelter Coating as a Preventive Conservation Method for Earthen Sites

Abstract

Shelter coating is a global practice implemented as one form of protection at earthen sites to reduce surface erosion of adobe. At Fort Union National Monument, the largest adobe site in the United States, shelter coating has been used since the 1980s and of various formulations and application methods. Current shelter coat practices at Fort Union consist of a two-coat system of an unamended layer of similar composition to the original adobe walls, followed by a second amended mud layer modified with a stabilizing agent (Rhoplex™ E-330) to enhance the exterior layer's water resistance and weatherability. Rhoplex™ E-330, an acrylic polymer emulsion, has been used at earthen sites across the Southwestern United States since the 1970s and began being tested for use in shelter coats at Fort Selden in the 1980s, and Fort Union in the early 2000s. Localized failures from cracking and loss leaving the original walls exposed and vulnerable, and increasing intensity of precipitation events due to a changing climate all argue for the current study of the practice and formulation of shelter coats at Fort Union. This thesis aims to examine earthen shelter coats applied as a method of preventive conservation to exposed adobe walls at archaeological or otherwise uninhabited heritage sites, with Fort Union National Monument in Watrous, New Mexico serving as the case study. Established in 1851, Fort Union was a military enclave and trade depot serving the Santa Fe Trail. Adobe served as the primary construction material at Fort Union given its regional availability and low cost. When Fort Union was abandoned in 1891, the adobe walls deteriorated significantly in part due to local despoiling which removed protective features and left the adobe walls exposed to the elements. Fort Union's "melting" adobe ruins remained unprotected until 1956 when the National Park Service began stabilization efforts. While formulas and application methods for shelter coats can vary, their performance should satisfy critical optimal properties identified through laboratory and field testing. In order of importance, these optimal properties include good consistency (plasticity), low shrinkage, good adhesion to the substrate (durability), good cohesive strength to resist erosion (durability), low liquid-water absorption, high desorption, moderate water-vapor permeability, and comparable color and texture to the substrate. This research identifies and evaluates performance parameters for earthen shelter coats and tests their efficacy in a series of lab-based simulations designed to characterize the soil, and then subject the soil to a series of performance tests to determine their properties. While the soils and amendments tested in this project are specific to Fort Union National Monument the methodology can be applied at any earthen site.

Keywords

earthen architectural heritage, shelter coat, Fort Union National Monument, preventive conservation, adobe

Disciplines

Historic Preservation and Conservation

Comments

AN EVALUATION OF SHELTER COATING AS A PREVENTIVE
CONSERVATION METHOD FOR EARTHEN SITES

Alison Cavicchio

A THESIS

in

Historic Preservation

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Frank G. Matero

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Section 1: Introduction

The global practice of applying a sacrificial layer or “shelter coating” to earthen architecture is used at many historic sites to protect and reduce surface erosion. In many climates and contexts, historic earthen ruins deteriorate more rapidly when left unprotected. Even when treated with a shelter coat, these structures require cyclical maintenance and monitoring. When there is cracking or loss of the shelter coat, the underlying earthen substrate, usually adobe or mudbrick, is exposed to the elements and the wall or floor surfaces become vulnerable to surface moisture and abrasion which can lead to loss and collapse. Worldwide, the formulas and application methods for shelter coats vary based on local materials and traditions, site management practices, and the use of amendments. Although the practice of shelter coating is widespread, there is no single formula that can be applied uniformly across sites as both the substrate and shelter coating are engineered using local soils which have distinct compositions with varying levels of sand, clay, and silt. While the soils and amendments tested in this project are specific to Fort Union National Monument in Watrous, New Mexico, the methodology can be applied at any earthen site.

Shelter coats are by design, renewable and therefore reversible through reapplication, a key consideration as practitioners make strides to link theory and practice in earthen heritage and embrace more sustainable conservation efforts.¹ The use of shelter coating is universal, but limited documentation exists about approaches to application and formulations, and even more rare is documented laboratory or field analysis to test soils and amendments prior to their use. At Fort Union National Monument and other earthen

¹ Louise Cooke, *Conservation Approaches to Earthen Architecture In Archaeological Contexts* (Oxford, UK: Archaeopress Publishers of British Archaeological Reports, 2010), 140, <https://doi-org.proxy.library.upenn.edu/10.30861/9781407306889>.

sites in the Southwestern United States, a myriad of surface treatments and shelter coat formulas have been used to protect adobe walls, yet scientific testing on shelter coating has not been conducted since the mid-1990s.² An evaluation of shelter coating practices is long overdue. At Fort Union (FOUN), the largest adobe site in the United States, shelter coating has been used since the 1980s and of various formulations and application methods. Localized failures from cracking and loss leaving the original walls exposed and vulnerable, and increasing intensity of precipitation events due to a changing climate all argue for the current study of the practice and formulation of shelter coats at Fort Union. This thesis aims to examine the performance of earthen shelter coats applied as a method of preventive conservation to exposed adobe walls at archaeological or otherwise uninhabited heritage sites, with Fort Union serving as the case study.

While formulas and application methods for shelter coats can vary, their performance should satisfy critical optimal properties identified through laboratory and field testing. These properties include good consistency (plasticity) and adhesion during application, optimal particle size distribution which results in low shrinkage, and good resistance to weathering including good cohesive strength (durability). Low liquid-water absorption, high desorption and moderate water-vapor permeability are also critical.³ To thoroughly evaluate shelter coating as a practice this research also examines deterioration mechanisms of adobe, the treatment history of Fort Union, and limited existing shelter

² Robert Hartzler and Anne B. Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report* (Santa Fe, NM: U.S. Department of the Interior, National Park Service, 1996), 30;

Robert Hartzler, *Holding Down the Forts: The Army, Adobe, and Preservation, Cultural Resource Management: Conserving Earthen Architecture* (Southwest Region: U.S. Department of the Interior, National Park Service, 1999), 55;

Anne Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report* (Los Angeles, CA: Getty Conservation Institute, and Museum of New Mexico, 2000), 20, http://hdl.handle.net/10020/gci_pubs/fort_selden_project.

³ Hugo Houben, and Hubert Guillaud, *Earth Construction: A Comprehensive Guide* (London, UK: Intermediate Technology Publications, 1994), 20;

Caroline Dickensheets, "A Performance Evaluation of Amended Stabilization Mortars at Wupatki National Monument, Arizona," (Master's Thesis, University of Pennsylvania, 2019), 1-185, https://repository.upenn.edu/hp_theses/680/.

coat testing. Laboratory testing was conducted to assess two Fort Union soils which have been alternately used for shelter coating since 2019 to present, and ultimately to evaluate the current shelter coat formula and test a modified formula with a lower percentage of the amendment Rhoplex™ E-330. The current research identifies and evaluates performance parameters for earthen shelter coats and tests their efficacy in a series of lab-based simulations designed to characterize the soil, and then subject the soil to a series of performance tests to determine their properties outlined above. This research will benefit sites where the historic adobe walls are permanently exposed for interpretation or other purposes.

A Brief History of Adobe

Adobe refers to the sundried mud bricks that are used, typically with earthen mortar, as a building technique throughout the world, but the term has also been used colloquially to describe the mud-based coating, or shelter-coating, that is often used as a finish. The word adobe is thought to be Arabic in origin, *atob*, which translates to sticky paste or muck.⁴ Interestingly though, the word is not used in the Middle East and North Africa region where some scholars believe the use of sun-dried mud brick may have started.⁵ Egyptian wall murals dating to 2500 BC show production techniques for adobe bricks described in hieroglyphics. The use of adobe spread from Egypt further into North Africa, to Roman cities, and to Spain via the Moorish invasion. Spanish settlers exported the building technique to the western hemisphere where it made its way to what is now

⁴ Paul Graham McHenry, *Adobe and Rammed Earth Buildings: Design and Construction* (New York, USA: John Wiley and Sons, 1984), 5.

⁵ *Ibid.*

the Southwestern United States.⁶ In the American Southwest adobe has several meanings: a house of mud brick, a brick, or mud plaster.⁷ Adobe bricks are made up of soil which contains coarse sand or aggregate, fine sand, silt, clay, and sometimes vegetal aggregates such as straw and manure, and amendments such as plant exudates or animal blood.⁸ Given their consistency, adobes are vulnerable to erosion if left exposed to the elements. As such, they must be protected with a finish, whether it be a lime, gypsum, or earthen plaster or an earthen shelter coat.

Shelter Coating in Theory and Practice

There are numerous approaches to conservation of earthen sites, each impacting the conservation and interpretation at the site.⁹ For example, at Fort Union the use of a large shelter structure, like the famous shelter designed by Frederick Law Olmsted, Jr. at Casa Grande National Monument, would significantly impact the visitor experience and the cultural landscape surrounding the ruins. Shelter coating can allow the site to be protected while maintaining important visual aesthetics.

Unlike stucco or plaster, shelter coats are not original to the architectural system. When contemporary adobe structures are in use they are typically plastered with clay, gypsum or lime plasters, or stucco. Yet as ruins, the use of these original renders is considered inappropriate as the structures are incomplete, missing critical structural elements of protection such as roofs, foundations, and stable wall elevations.¹⁰ Stabilizing

⁶ McHenry, *Adobe and Rammed Earth Buildings*, 6.

⁷ *Ibid.*

⁸ *Ibid.*, 7.

⁹ Cooke, *Conservation Approaches to Earthen Architecture In Archaeological Contexts*, 25.

¹⁰ Mariana Rita Correia and Alberto Rosado, *Conservation in Earthen Heritage: Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies* (Cambridge, UK: Cambridge Scholars Publishing, 2016), 58, <https://www.researchgate.net/publication/303459709>.

remaining plaster fragments on archaeological adobe is appropriate and has been conducted at Fort Union and other sites; however, these original fragments rarely provide the protection they once did. The process of re-plastering archaeological adobe as a protective mechanism is not a viable option in many cases as the ruined walls were never fully plastered in their current state and often the application of plaster requires replacing many of the original adobes. To achieve this at an earthen ruin such as Fort Union would mean removing a significant amount of the original fabric, thereby counteracting the goal of conserving the remaining adobe. Restoring original surfaces on fragmented walls would be contradictory in this case given that conservation at the site requires maintaining the ruins as is, “preserving and protecting,” not reconstructing or rehabilitating them.¹¹ Shelter coating avoids this contradiction by protecting the surface while maintaining the visibility of its current form for interpretation and conservation purposes.

A shelter coat typically consists of one or two layers, sometimes including an unamended mud layer applied directly to the adobe wall, followed by an amended mud layer that includes a natural or synthetic amendment to enhance water resistance of that exterior layer. Natural mud shelter coats are both inexpensive, readily available in the regions in which they are used, and environmentally friendly. If the shelter coat is working as it should, the shelter coat erodes first rather than the original adobe surface. The Preservation Action Plan published by FOUN in 1996 noted that shelter coat treatment was a critical factor to the survival of adobe walls, in addition to original wall

¹¹ U.S. Department of the Interior, National Park Service, “Appendix A: Enabling Legislation for Fort Union National Monument, United States Senate and House of Representatives 1954” *In Foundation Document, Fort Union National Monument, New Mexico* (Watrous, NM: National Park Service, 2014), https://www.nps.gov/foun/learn/management/upload/FOUN_FD_FINAL.pdf.

thickness, orientation and exposure, wall configuration and supports, and capping treatments.¹²

The term shelter coat is used infrequently in publication and appears primarily in literature about conservation of adobe in the Southwestern United States. Of note are the different terms used throughout the literature to describe finishes used to protect contemporary and historic earthen architecture and archaeological ruins, including mud or earth plaster, rendering, and plaster. In the field, the terms shelter coat and plaster are often used interchangeably at archaeological sites. On site, plastering is accepted as another term for shelter coating, yet in the literature, the general reference to “plaster” can be misleading and confusing, as it is unclear if the reference being made is to an original feature of the site regardless of its composition or whether it refers to a new sacrificial layer added for protection. The literature shows that non earthen renders have been used on historic earthen sites in the past, but these materials can reduce permeability, often causing more damage to the underlying adobe by trapping moisture between the render and the original adobe. Cement and lime stabilized shelter coats are not appropriate for historic earthen buildings, particularly at archaeological sites which are missing critical structural elements of protection.¹³ Defining the difference between these terms, as described below, is necessary to understand why shelter coating is a distinct practice that requires further study.

Rendering or Plaster: Earth, stabilized earth, or clay and sand-based mortar to which a hydraulic binder or cement, lime or other additive (bitumen, resin, etc.) has been added.

¹² Robert Hartzler and Anne B. Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report (Test Walls Program)* (Santa Fe, NM: U.S. Department of the Interior, National Park Service, 1996), 2.

¹³ Correia and Rosado, *Conservation in Earthen Heritage: Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies*, 62.

Renderings may be applied in a single layer or in several layers.¹⁴ Render is also called plaster when referring to lime or gypsum plasters that are applied with edging and require a stabilized wall for attachment.

Mud or earth plaster: Traditionally a mixture of clay, sand, water, and a local aggregate or admixture (cow dung, grass, straw, etc.), applied to the interior or exterior adobes. Chopped straw as a stabilizer is the most common aggregate, used all over the world.¹⁵ It should be noted that mud plaster is used alone as a finish on inhabited structures in remote areas where renders or plasters are cost prohibitive or otherwise unavailable. The composition of this mud plaster is like adobe, making its properties compatible to those of the original adobe.¹⁶ Much of the testing to date on mud plaster is for finished or sheltered earthen structures and contains an admixture.¹⁷

Earth Mortars: Recent literature refers to earth mortars defined as “Earth-based mixes intended to produce mud-bricks, plasters, renders or masonry mortars.”¹⁸

Unamended Plaster: At Fort Union National Monument, a mud plaster is mixed without a local additive or admixture. This is referred to as unamended mud plaster.¹⁹

Amended Plaster: The term “impregnation” was used by Houben to describe soil with a natural or chemical product added to confer impermeability and harden the wall

¹⁴ Houben and Guillaud, *Earth Construction*, 335.

¹⁵ Straw as an additive is typically not used on archaeological shelter coats at FOUN given its propensity to attract insects or wildlife.

¹⁶ U.S. Department of the Interior, National Park Service, Heritage Preservation Services, *Preservation Brief 5: Preservation of Historic Adobe Buildings*, 1978, <https://www.nps.gov/tps/how-to-preserve/briefs/5-adobe-buildings.htm#coatings>.

¹⁷ Tania Santos, Paulina Faria and Vitor Silva, “Can an earth plaster be efficient when applied on different masonries?” *Journal of Building Engineering* Volume 23, May 2019: 314-323, <https://doi.org/10.1016/j.jobbe.2019.02.011>;

Matthieu Pedernana and Soofia Tahira Elias-Ozkan, “Impact of various sands and fibres on the physical and mechanical properties of earth mortars for plasters and render,” *Journal of Construction and Building Materials*, Volume 308: Available Online October 4, 2021: 1-21, <https://doi.org/10.1016/j.conbuildmat.2021.125013>.

¹⁸ *Ibid.*, 2.

¹⁹ Masonry Mixes 2018, “Conservation, Preservation Work” (unpublished manuscript, Fort Union National Monument Administrative Office, Watrous, New Mexico, last modified 2018), Scanned PDF file.

surface. The impregnated plaster is applied by hand, by spraying, or with a brush to the adobe walls.²⁰ In contemporary terms this is referred to as amended soil or mud plaster.

Shelter Coat: A shelter coat is applied to exposed original adobe walls at archaeological sites to protect the wall from further damage by wet and dry erosion. A shelter coat is composed of and applied in two layers at Fort Union National Monument: an unamended mud plaster is applied directly to the original adobe, followed by a layer of amended plaster (called the “topcoat mud plaster” by Fort Union).²¹ The unamended mud plaster applied directly to the adobe is intended to offer release of the amended layer without damage to the adobe substrate beneath.



Figure 1: Exposed Adobe at FOUN 1954 (Wilson).²²

²⁰ Houben and Guillaud, 348.

²¹ Masonry Mixes 2018.

²² Rex Wilson, *Fort Union National Monument Ruins*, National Park Service, 1954.



Figure 2: Shelter Coated Adobe at FOUN 2021 (Photo by author).

Section 2: Site Context

In 1846, New Mexico was ceded to the United States via the Treaty of Guadalupe, effectively ending the Mexican American War and establishing the U.S. presence in the region. The federal government began constructing military forts in the Southwest to assert dominance in the newly acquired territory, one of which was Fort Union.

Established in 1851, Fort Union was a military enclave and trade depot serving the Santa Fe Trail, an outpost during the Civil War and later Indian Wars. Three phases of Fort Union were constructed, beginning in 1851. The ruins that remain today were part of the third Fort Union, which was constructed in 1863 and ultimately abandoned in 1891.²³

Today, Fort Union preserves the region's military history as well as that of the local Hispano and Native American populations who worked at and were displaced by the Fort's construction. Fort Union's darkest history includes the Long Walk, a campaign led by Kit Carson in 1863 where thousands of the Deney, later renamed the derogatory term 'Navajo' by settlers, were marched through Fort Union during their forced resettlement.²⁴

²³ Dwight T. Pitcaithley and Jerome A. Greene, *Historic Structure Report, Historical Data Section, The Third Fort Union, 1863-1891* (Fort Union National Monument, New Mexico: National Park Service, June 1982), 1-40.

²⁴ Fort Union National Monument Site Visit and Tour, Recorded by Alison Cavicchio, University of Pennsylvania, October 11, 2021.



Figure 3: Unidentified infantry soldiers and officers sitting in front of post headquarters the third Fort Union, late 1880s.²⁵



Figure 4: A view of officers' row at Fort Union.²⁶

²⁵ U.S. Department of the Interior, National Park Service, "Chapter 8: Life at the Third Fort Union" In *Fort Union Historic Resource Study* (Watrous, NM: National Park Service, 2005), https://www.nps.gov/parkhistory/online_books/foun/chap8.htm.

²⁶ Fort Union National Monument, *Third Fort Union – Officers Row*, National Park Service, <https://www.nps.gov/media/photo/view.htm?id=C6A0F803-155D-451F-67A6F829CAAF3773>.

On June 28, 1954, after sixty-three years of abandonment beginning in 1891, Congressional legislation mandated the establishment of Fort Union (FOUN) as a National Monument to be preserved and protected under the authority of the Secretary of the Interior.²⁷ Fort Union National Monument is in Mora County, Watrous, New Mexico, approximately ninety-five miles northeast of Santa Fe. After the Tenth Infantry marched out of Fort Union for good in February 1891, the title for the Mora Land Grant on which Fort Union sat eventually passed to the Butler-Ames Cattle Company. For unknown reasons, a contract to turn the fort into a sanitarium was never fulfilled, and the company made no attempts to use or rehabilitate the fort “except to open it to cattle grazing.”²⁸ After years of neglect Fort Union’s adobe and stone walls and wooden structures had deteriorated significantly, in part due to local despoiling which removed timber, roofing, windows, and doors, leaving the adobe walls of the third fort exposed to the elements.²⁹ According to Fort Union’s administrative history, “Whenever a family wanted to repair or even to build a house, the people went to the ruins of Fort Union to find what they needed. In Watrous, almost all the windows, doors, and vigas in the houses came from Fort Union.”³⁰ Sun dried mud brick, regionally known as adobe in the American Southwest, served as the primary construction material at Fort Union given its regional availability and low cost. With the removal of protective elements and destabilization of the walls, the buildings succumbed to further weathering. A report by the Santa Fe Regional National Park Service in 1939 noted that the buildings should not be restored or

²⁷ U.S. Department of the Interior, National Park Service, “Appendix A.”

²⁸ Liping Zhu, *Fort Union National Monument: An Administrative History*, (Santa Fe, NM: U.S Department of the Interior, National Park Service, 1992), 14.

²⁹ Robert Hartzler and Anne Oliver, 2000, “Understanding the Deterioration of Adobe Walls: Fort Union National Monument,” In *Preprints of Terra 2000 8th International Conference on the Study of Conservation of Earthen Architecture*, Torquay, Devon, UK, May 2000, 78-85. London, UK: James and James.

³⁰ Zhu, *Fort Union National Monument: An Administrative History*, 14.

reconstructed.³¹ This recommendation was ultimately codified by law when the congressional legislation mandated that the ruins should be stabilized and preserved for public education and inspiration,³² thereby limiting the conservation interventions that were to be carried out by the National Park Service. In 1958 the National Survey of Sites and Buildings along the Santa Fe Trail noted the “melting adobe ruins of Fort Union.”³³



Figure 5: Aerial view of the site of Fort Union's second (star fort) and third fort (rectilinear) ruins (1933).³⁴

In 1956 the National Park Service began archaeological excavation and stabilization of the exposed adobe walls of Fort Union as per the congressional mandate

³¹ Aubrey Neasham and Hillory A. Tolson, *Special Report: The Proposed Fort Union National Monument* (Southwest Regional Office: U.S. Department of the Interior, National Park Service, File L-58, June 1939).

³² Evan Medley, ““Particularly New Mexico’s Monument”: Place-Making at Fort Union 1929-2014,” (A Dissertation Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy, Arizona State University, 2016), 95-163, https://keep.lib.asu.edu/flysystem/fedora/c7/153971/Medley_asu_0010E_15939.pdf.

³³ U.S. Department of the Interior, National Park Service, *The National Survey of Historic Sites and Buildings Report on the Santa Fe Trail*, 1958.

³⁴ “Fort Union, State Highway No. 161, Watrous, Mora County, NM,” Historic American Buildings Survey, documentation compiled after 1933, <https://www.loc.gov/resource/hhh.nm0172.photos>.

two years earlier. From 1956 to present numerous iterations of conservation methods to preserve the adobe walls have been tested and used at the site, ranging from then new synthetic resins to the use of amended mud shelter coats applied directly to the original adobe.

Fort Union is located at an elevation of 6,700 feet in a semi-arid zone with historically moderate temperatures without great extremes of heat or cold. Despite being a semi-arid climate, the Mora Valley receives enough rainfall to support vegetation including juniper, pinon pine, and blue grama grass, and over fifty species of animals live in the area.³⁵ In recent years FOUN staff have noted more severe weather events in the region, including extreme cold, hail, and intense rainstorms that impact the condition of the fragile adobe ruins.

³⁵ Zhu, 1-164.

Section 3: Research Methodology

The methodology for this project included a site visit, consultations with FOUN staff, archival and materials research, and materials testing at the Architectural Conservation Lab at the University of Pennsylvania.

1. Site Visit and Consultations

A site visit was conducted in October 2021. The field visit portion of this study was critical to understand current shelter coat mixes and application methods. Interviews were conducted with park staff while on site at Fort Union. Follow up interviews were carried out when lab testing began in Philadelphia in January 2022 to confirm the ratios of materials needed for the shelter coats, and to confirm the consistency of the mixes with the identified ratios. Details from these interviews informed and are recorded as part of the contemporary phases of the treatment history at Fort Union (Section 5).

In addition to identifying the shelter coat practices currently applied at FOUN the purpose of the site visit was also to document observations about the shelter coat performance including failures (Appendix A):

- Historic Structure Report (HSR) number/site name
- Room number, interior or exterior
- Cardinal direction of the wall face
- Date of last shelter coating based on the site visit in October 2021
- Number of layers of the shelter coating
- Total thickness of the shelter coating
- Failure mode: interlayer separation between the shelter coat and adobe support, or intralayer between two layers of shelter coats

- Cracking
- Presence of moisture below the spalled shelter coats

For the current research these details primarily informed the lab testing component to ascertain the thickness at which one shelter coat is applied since it is not applied uniformly at FOUN. The full details of these observations can be found in Appendix A.

2. Archival and Materials Research

The literature review, which is laid out in detail in Section 4, includes research on earthen conservation approaches and theories, existing shelter coat or mud plaster testing conducted to date, and deterioration mechanisms of adobe to inform what the optimal properties of a shelter coat should be.

The treatment history of Fort Union (Section 5) includes archival research and documents from FOUN's administrative office in Watrous, New Mexico. This chapter includes research regarding previous and current surface treatment methods, interviews with Fort Union staff, and what existing shelter coat formulas and application methods look like at FOUN today. Research about testing of earthen grouts and mortars from previous University of Pennsylvania Historic Preservation theses³⁶ and studies conducted by National Park Service staff and the Getty Conservation Institute on field tests for soil ultimately informed the lab testing program.

³⁶ Dickensheets, "A Performance Evaluation of Amended Stabilization Mortars at Wupatki National Monument, Arizona," 1-185; Nityaa Lakshmi Iyer, "Performance Evaluation of Clay Grout Formulations for Structural Cracking in Historic Earthen (Mud Brick) Buildings." (Master's Thesis, University of Pennsylvania, 2014), 1-125, https://repository.upenn.edu/hp_theses/561/; Robert Lyle Hartzler, "A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites," (Master's Thesis, University of Pennsylvania, 1996), 1-372, https://repository.upenn.edu/hp_theses/367/; William A. Zinn, "Cement Modified Earthen Mortar- An Investigation of Soil-Cement Performance Characteristics at Three Southwestern National Monuments," (Master's Thesis, University of Pennsylvania, 1996), 60-62, http://repository.upenn.edu/hp_theses/44/.

3. Preliminary and Confirmatory Performance Laboratory Tests

A series of lab tests were identified to test for the optimal properties of the shelter coat formulations. Given the time constraints of the thesis schedule, not all the tests initially proposed were carried out, but the full testing program is included in the developed testing matrix for the future (Appendix B). The following tests were prioritized based on critical optimal properties for shelter coats and were carried out between January and April 2022. The results of the soil characterization (Section 6) informed which soil moved forward into the preliminary and performance test stages.

Soil Characterization of Red and Brown Soils:

- Particle size analysis (dry and wet sieve): ASTM D7928-21e1 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis.
- Liquid and Plastic Limits (Atterburg Limits): ASTM D4318-17e1 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.
- Salt Concentration: MQuant tabs were used to obtain measurements.
- pH Test: ASTM D4972-19 Standard Test Methods for pH of Soils.
- Carbonate Content: ASTM D4373-21 Standard Test Method for Rapid Determination of Carbonate Content of Soils.
- Methylene Blue Adsorption Test: Modified AFNOR NF P 94-068-1998.

Performance Tests on Brown Soil

- Shrinkage: Qualitative clay saucer test.

- Consistency or Slump Test: ASTM C230 Standard Specification for Use of Flow Table and ASTM C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar.³⁷
- Water Drop, Depth of Erosion: Standard developed by CraTerre for soils.
- Water Drop, Absorption: UNESCO, Rilem, developed standard.

³⁷ Zinn, "Cement Modified Earthen Mortar- An Investigation of Soil-Cement Performance Characteristics at Three Southwestern National Monuments," 60-62.

Section 4: Literature Review

Shelter coating is an observed practice around the world, from the Southwestern United States to West Africa, the Middle East, Central Asia, and Asia.³⁸ Despite its widespread applicability and use, the concept of shelter coating is mentioned infrequently in earthen conservation literature, and direct research on the topic is nearly absent. The term shelter coat appears primarily in literature pertaining to earthen conservation in the Southwestern United States (see Section 1: Introduction for defined terms). Three distinct areas of research inform the concept of the shelter coat as a mechanism for protecting archaeological adobe walls. These include: 1) history and development of shelter coating as a practice, 2) material properties of adobe and associated decay mechanisms, and 3) testing of surface treatments, including characterization of soils and performance testing of shelter coats. Conservation of earthen sites has evolved significantly over the last thirty-five years, yet there is much to be explored and published, particularly on the topic of shelter coats.

³⁸ Cooke, 140.

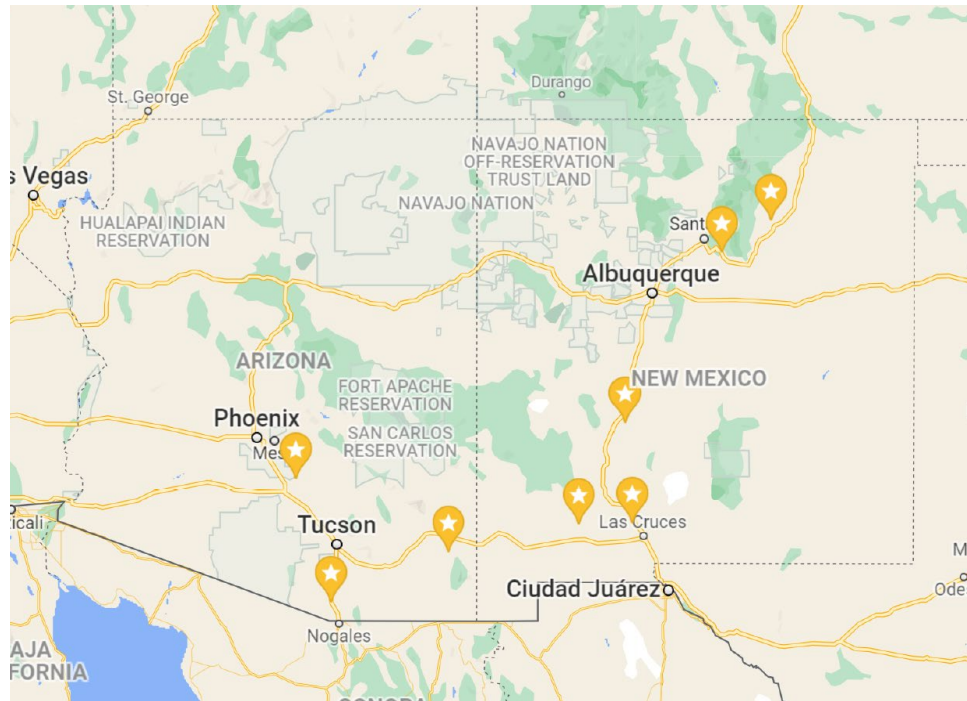


Figure 6: Sites using shelter coating as a technique in the Southwestern United States (by author).



Figure 7: Sites using shelter coating as a technique in Central Asia (By author, Central Asian sites based on Louise Cooke's 2010 dissertation).³⁹

³⁹ Cooke, 140.

1. History and development of shelter coating as a practice

Earthen conservation research and practice revolves primarily around five main bodies: the Terra World Congress on Earthen Architectural Heritage under the aegis of the International Council on Monuments and Sites' International Scientific Committee on Earthen Architectural Heritage (ICOMOS-ISCEAH), the U.S. National Park Service, the Getty Conservation Institute, CRAterre- the International Center for Earthen Architecture, and the World Heritage Earthen Architecture Programme (WHEAP). Yet, unlike other areas of conservation, there is no charter or regulating body specific to earthen heritage. Recommendations are provided during the Terra World Congress on Earthen Architectural Heritage, yet they are not always implemented in a uniform manner.⁴⁰ Various approaches to conservation of earthen sites exist in theory and in practice, and like other areas of conservation, reversibility is a major concern at earthen sites.⁴¹ A range of practices are implemented around the world based on material considerations and the theoretical questions surrounding the structures and sites.⁴² These include backfilling, capping and encapsulation, consolidation, 'do nothing,' draining and undercut, maintenance (including shelter coating), reconstruction and restoration, removal/relocation, and sheltering (see Figures 8-12).⁴³ Selection of approach must be based on careful consideration of site significance, materials, environmental and man-made factors, maintenance, systems present, and treatment predictability.⁴⁴ While site

⁴⁰ Correia and Rosado, 88.

⁴¹ *Ibid.*

⁴² Cooke, 17.

⁴³ Erica Avrami, et al., *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation* (Los Angeles, California: J. Paul Getty Trust: The Getty Conservation Institute, 2008), https://www.getty.edu/conservation/publications_resources/pdf_publications/terra_literature_review.html, 1-174; Cooke, 17.

⁴⁴ Frank Matero, "A programme for the conservation of architectural plasters in earthen ruins in the American Southwest," *Conservation and Management of Archaeological Sites*, Volume 1 (1995): 5-24.

specific challenges and needs dictate the course of preventive treatment that is employed, research in earthen conservation is lacking and dedicated laboratory and field testing is needed.⁴⁵

While the field of earthen conservation has grown substantially over the years, there is little research explicitly focused on the practice of shelter coating earthen archaeological sites. There is some published literature regarding mud capping as a preventative protection mechanism for adobe.⁴⁶ Mud capping is associated with current shelter coat practices at Fort Union National Monument and other sites in the Southwestern United States but can also include capping with new adobe bricks layered with a shelter coat. To date, there is extensive research on the concept of sheltering as a preventive conservation approach, despite its limited applicability at many earthen heritage sites.⁴⁷ Shelter coating, while less invasive to the substrate and the visual cultural landscape, remain largely unstudied compared to other approaches.

Shelter coating is a distinct practice from mud plastering of inhabited adobe in that shelter coating is a sacrificial layer used to protect archaeological adobe or otherwise uninhabited sites that have lost protective structural elements. Earthen buildings such as the 13th century Mosque of Djene in Mali, the Taos Pueblo in New Mexico, and the

⁴⁵ Mariana Rita Correia, Luis Guerrero and Anthony Crosby, "Technical Strategies for Conservation of Earthen Archaeological Architecture," *Conservation and Management of Archaeological Sites*, Volume 17, No. 3 (2015): 224-256, <https://www.tandfonline.com/doi/abs/10.1080/13505033.2015.1129799>;

Avrami, et al., *Terra Literature Review*, 1-174;

Claudia Cancino, "It Always Takes a Village: Preserving Earthen Sites," *Structural Analysis of Historical Constructions: RILEM Bookseries*, Volume 18 (2019): 44-56, https://link-springer-com.proxy.library.upenn.edu/chapter/10.1007/978-3-319-99441-3_4.

⁴⁶ Hartzler and Oliver, "Understanding the Deterioration of Adobe Walls: Fort Union National Monument," 78-85;

Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 1-108;

Anne Oliver, "Conservation of Earthen Archaeological Sites" In *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation*. (Los Angeles, California: J. Paul Getty Trust: The Getty Conservation Institute, 2008), 80-96. https://www.getty.edu/conservation/publications_resources/pdf_publications/terra_literature_review.html.

⁴⁷ Zaki Aslan, et al, eds. 2018, "Protective Shelters for Archaeological Sites," In *Proceedings of a Mosaikon Symposium, Herculaneum, Italy, September 23-27, 2018, London, UK*: The British School at Rome, https://www.iccrom.org/sites/default/files/publications/2018-11/protectiveshelters_web_rev.pdf;

Oliver, "Conservation of Earthen Archaeological Sites," 80-96; Cooke, 1-160.

Churches of San Francisco de Asis de Marcapata, and Kuchuwasy, in Cusco, Peru, share a noteworthy attribute in that “they were constructed with the idea of being maintained by the community who erected and used them.”⁴⁸ Shelter coating diverges from this practice as a distinct form of preventive conservation that was developed as a response to the problem of protecting earthen ruins. Earthen ruins are one of the most intractable problems that the field of built heritage conservation is confronted with; “Lacking the very architectural devices originally in place to combat and control weathering, earthen ruins face rapid deterioration without constant remedial and preventive conservation.”⁴⁹ In 1980, the first formal research project to test shelter coating as a protective mechanism for earthen ruins was carried out at Fort Selden in New Mexico.⁵⁰ At the same time, Fort Union began informally field testing unamended shelter coats in the 1980s, and amended shelter coats in the early 2000s (see Section 5: Treatment History). Earthen conservation research specific to approaches, including shelter coating, and enhanced technical capacity in the field of earthen heritage is necessary.⁵¹

⁴⁸ Cancino, “It Always Takes a Village: Preserving Earthen Sites,” 44-56.

⁴⁹ Frank Matero, “Mud Brick Metaphysics and the Preservation of Earthen Ruins,” *Conservation and Management of Archaeological Sites*, Volume 17, No. 3: (2015): 209–223, <https://www.tandfonline.com/doi/abs/10.1080/13505033.2015.1129798>.

⁵⁰ Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 1-108;

⁵¹ Avrami, et al., 1-174;
Cancino, 44-56.



Figure 8: Sheltering: Casa Grande Ruins National Monument, AZ (NPS).⁵²



Figure 9: Maintenance: Bracing on Shelter Coated Walls at FOUN (CAC).⁵³

⁵² U.S. Department of the Interior, National Park Service, *Casa Grande Ruins National Monument, AZ, a distinct example of the concept of sheltering*, <https://www.nps.gov/cagr/index.htm>.

⁵³ Center for Architectural Conservation, *Bracing on Shelter Coated Walls*, CAC, http://www.conlab.org/acl/foun/foun_summary.html.



Figure 10: Backfilling: Backfilled rooms at Pecos, NM (Cooke).⁵⁴



Figure 11: Reconstruction and Encapsulation: Nisa, Turkmenistan (Cooke).⁵⁵

⁵⁴ Cooke, 144.

⁵⁵ *Ibid.*, 145.



Figure 12: Encapsulation: Excavation of encapsulated adobe (original adobe protected by encapsulation is outlined in yellow) at Pecos National Historical Park 2021 (Photo by author).

2. Material Properties of Adobe and Associated Decay Mechanisms

Shelter coating protects archaeological adobe which has been left exposed to the elements. Adobe bricks are not kiln fired making them unstable and particularly susceptible when the shelter coat fails, and they are exposed to moisture.⁵⁶ This point underscores why the study of shelter coating as a distinct practice within earthen heritage is critical. Reference books and materials on earthen construction, conservation of historic adobe buildings, the material properties of soil and adobe, including types of clay and clay minerals, and their properties, are the basis on which conservation of earthen heritage relies.⁵⁷ Conference and training publications, and regional references provide

⁵⁶ Matero, "Mud Brick Metaphysics and the Preservation of Earthen Ruins," 209–223; U.S. Department of the Interior, *Preservation Brief 5: Preservation of Historic Adobe Buildings*.

⁵⁷ McHenry, 1-125; Houben and Guillaud, 3-359; Gernot Minke, *Building with Earth: Design and Technology of a Sustainable Architecture* (Basel, Switzerland: Birkhäuser Verlag, Basel, 2013), 9-205;

insight into specific practices in earthen construction and techniques, and are also useful guides for regional terminology and in some cases technical recommendations specific to a particular region.⁵⁸

There is an abundance of literature that reviews the decay mechanisms and rapid deterioration associated with adobe and the challenges of preserving earthen sites.⁵⁹ These publications are found in site specific reports and civil engineering or construction journals, and detail the most important elements in the survival of an adobe wall, including original wall thickness, orientation and exposure, wall configuration and supports, capping treatments, and shelter coat treatments, as well as conditions that threaten adobe walls (shouldering, basal erosion, leaning, and coving).⁶⁰ Basal erosion in particular may be exacerbated when impervious coatings are used at the base as the coatings force moisture to rise through the wall.⁶¹ The impervious coating forces moisture to rise up the wall before it can escape and evaporate, causing moisture-related

John Warren, *Conservation of Earth Structures* (Oxford, UK: Butterworth-Heinemann, 1999), 1-194;

Avrami, et al., 1-174;

Alison Henry et al, *Earth Brick and Terracotta* (Farnham, Surrey, England: Historic England, Ashgate Publishing Limited, 2015), 1-350.

⁵⁸ Edward Smith, *Adobe Bricks in New Mexico* (Socorro, NM: New Mexico Bureau of Mines and Mineral Resources, 1982), 7-89; George Austin, 1990, "Adobe and related building materials in New Mexico," In *Adobe 90 Preprints of the 6th International Conference on the Conservation of Earthen Architecture, Las Cruces, New Mexico, October 14-19, 1990*. Las Cruces, NM: The Getty Conservation Institute, 417-423, https://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/adobe90_1.pdf; Saverio Mecca and Letizia Dipasquale, *Earthen Domes et Habitats: Villages of Northern Syria, an architectural tradition shared by East and West* (Florence, Italy: European Commission, Education, Audiovisual and Culture Executive Agency, Culture Programme 2000, 2009), 11-474; Cooke, 1-160;

World Heritage Programme on Earthen Architecture (WHEAP), *World Heritage Inventory of Earthen Architecture* (Paris, France: UNESCO, 2012). <https://whc.unesco.org/en/news/879>.

⁵⁹ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 1-186;

Rogiros Illampas, Ioannis Ioannou and Dimos C. Charmpis, "Overview of the Pathology, Repair and Strengthening of Adobe Structures," *International Journal of Architectural Heritage*, 7:2 (2013): 165-188, <https://doi.org/10.1080/15583058.2011.624254>; Matero, "Mud Brick Metaphysics and the Preservation of Earthen Ruins," 209-223;

Umaima Al Aqtash and Paola Bandini, "Prediction of Unsaturated Shear Strength of an Adobe Soil from the soil-water characteristic curve," *Construction and Building Materials Journal*, Volume 98 (2015): 892-899, <https://doi.org/10.1016/j.conbuildmat.2015.07.188>;

Correia, Guerrero and Crosby, "Technical Strategies for Conservation of Earthen Archaeological Architecture," 224-256; Correia and Rosado, 1-224;

J. Richards et. al, "A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain," *Heritage Science*, Volume 7, No. 51: (2019): 892-899, <https://doi.org/10.1186/s40494-019-0293-7>.

⁶⁰ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 1-186.

⁶¹ Al Aqtash and Bandini, "Prediction of Unsaturated Shear Strength of an Adobe Soil from the soil-water characteristic curve," 892-899;

deterioration at higher levels of the wall. Moisture retention at the wall base due to these water impermeable applications can also cause the wall base to remain wet thereby reducing its strength, resulting in deformation and possible collapse.⁶² Earthen ruins are incredibly difficult to maintain unprotected because earth as a building material is vulnerable to moisture from precipitation, melting snow, rising or falling damp, and surface condensation. Shelter coating alone will not suffice in protecting adobe walls; other factors at play must be considered in practice at Fort Union or any other earthen ruin.⁶³

3. Testing of surface treatments

There is significant documentation of surface treatments employed to conserve the adobe walls at Fort Union National Monument from 1956 to the present (see Section 5: Treatment History).⁶⁴ More broadly, there is a lack of dedicated testing of earthen materials and published research, while adaptations to in situ field work are limited as a result of the dearth of laboratory and field testing.⁶⁵ The lack of knowledge in situ of soil behavior and its relationship with other materials and the broader systems of earthen architectural heritage can “result in the misapplication of conservation methods and materials.”⁶⁶ To address this problem, greater links between field and laboratory testing

⁶² *Ibid.*

⁶³ Matero, “Mud Brick Metaphysics and the Preservation of Earthen Ruins,” 209–223.

⁶⁴ Roland Richert and Gordon Vivian, *Ruins Stabilization in the Southwestern United States* (Washington, DC: U.S. Department of the Interior, National Park Service, 1974), 1-139, https://www.nps.gov/parkhistory/online_books/archeology/10/contents.htm; Zhu, 1-164;

Jocelyn Kimmel and Frank Matero, “An Outline History of Stabilization and Conservation Treatments: Fort Union National Monument” (unpublished manuscript for the U.S. Department of the Interior National Park Service Intermountain Cultural Resources Center, Santa Fe, New Mexico, last modified 1995), Scanned PDF file; Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 1-186; Robert Hartzler and Anne Oliver, 2000, “Learning from the Site: Evolution of the Fort Union Strategic Preservation Plan,” In *Preprints of Terra 2000 8th International Conference on the Study of Conservation of Earthen Architecture*, Torquay, Devon, UK, May 2000, 39-45. London, UK: James and James.

⁶⁵ Correia, Guerrero and Crosby, 224-256;

Correia and Rosado, 1-224;

Cancino, 44-56.

⁶⁶ Correia, Guerrero and Crosby, 224-256.

are needed, as is enhanced dialogue between practitioners across earthen construction and conservation.⁶⁷ Laboratory test standards including the characterization of soils and performance tests are critical tools in the study of shelter coating.

Characterization of soils through compositional and performance testing has been developed according to different industry standards. Earthen heritage applications most commonly utilize geotechnical standards developed for engineering purposes. Characterization testing references include ASTM standards for particle-size distribution of fine grained soils, and ASTM standards for the liquid limit, plastic limit, and plasticity index of soils.⁶⁸ Additional confirmatory tests utilized for soil characterization include ASTM standards for carbonate content, and pH, and a modified standard from the French Standardization Association (AFNOR) for methylene blue adsorption to determine clay content.⁶⁹ Performance testing to determine soil consistency closely follows ASTM standards, including the use of a flow table.⁷⁰ Yet performance test standards have also been developed by organizations such as UNESCO and Rilem, and CRATERre, who developed specific tests for soils including the water drop absorption (microdrop) and water drop erosion tests respectively.⁷¹ Given that testing soils for archaeological or architectural heritage purposes have a different set of needs than those conducted for engineering purposes, academics and architectural conservators have adapted many of the

⁶⁷ Avrami, et al., 1-174.

⁶⁸ “D7928-21e1 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis,” (West Conshohocken, PA: ASTM, 2021);

“D4318-17, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils,” (West Conshohocken, PA: ASTM, 2017).

⁶⁹ “D4972-19 Standard Test Methods for pH of Soils,” (West Conshohocken, PA: ASTM, 2019);

“D4373-21 Standard Test Method for Rapid Determination of Carbonate Content of Soils,” (West Conshohocken, PA: ASTM, 2021).

⁷⁰ “C 230/C230M-21: Standard Specification for Flow Table for Use in Tests of Hydraulic Cement,” (West Conshohocken, PA: ASTM, 2021);

“C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar,” (West Conshohocken, PA: ASTM, 2020).

⁷¹ UNESCO, Rilem, “Water drop absorption,” In *International Symposium on Deterioration and protection of stone monuments: experimental methods*. Paris, France, Volume V, Test II. 8b: (1978): Teutonico’s *A Laboratory Manual for Architectural Conservators*, 42-45; Zinn, 60-62.

tests noted above. In some cases, earthen conservation practitioners created their own tests as is the case with CRAterre's water drop erosion, and a qualitative clay saucer test designed to measure shrinkage in soils, developed by the University of Pennsylvania.⁷²

Published literature regarding testing of adobe bricks and mortars with unamended and amended elements to test for moisture resistance is widespread and can inform research and testing of developed shelter coat formulations.⁷³ Tests using Rhoplex™ E-330 amended mortars at Fort Union and Wupatki National Monuments provide insight into the use of Rhoplex™ E-330 as a shelter coat amendment.⁷⁴ The Fort Selden Test Wall Project tested surface coatings on adobe walls and is an invaluable resource as one of the only publications dedicated to field testing of shelter coats. Research associated with archaeological plasters and conservation of finishes on earthen substrates can also inform the testing methods for shelter coats.⁷⁵

Recent testing of surface treatments and earthen plasters in engineering journals has focused on earthen structures protected by sound architectural elements and focus on new construction using earthen plasters as an environmentally 'green' building material and not as a conservation mechanism

⁷² Qualitative Shrinkage Test using terracotta saucers, by the University of Pennsylvania's Architectural Conservation Laboratory.

⁷³ Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 1-108.

Marco Antonio Penido d Rezende and Jacqueline Leite Ribiero do Vale, 2016, "Adobe with 1 % clay and 2.11 MPa resistance: a case study," In *Terra Lyon 2016 Proceedings of the 12th World Congress on Earthen Architecture, Lyon, France, July 11-14, 2016*. Lyon, France: CRAterre, https://craterre.hypotheses.org/files/2018/05/TERRA-2016_Th-4_Art-220_Rezende.pdf;

Serena Love, "Field Methods for the Analysis of Mud Brick Architecture," *Journal of Field Archaeology*, 42:4 (2013): 351-363, https://www.researchgate.net/publication/318350364_Field_Methods_for_the_Analysis_of_Mud_Brick_Architecture;

Caroline Dickensheets and Frank Matero, "Performance Testing of Acrylic- Amended Earthen Mortars at Wupatki National Monument in Arizona," *Bulletin of the Association for Preservation Technology*, Volume 52, No. 1 (2021): 5-13.

⁷⁴ Hartzler, "A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites," 1-372;

Dickensheets and Matero, "Performance Testing of Acrylic- Amended Earthen Mortars at Wupatki National Monument in Arizona," 5-13.

⁷⁵ Frank Matero, "A programme for the conservation of architectural plasters in earthen ruins in the American Southwest," *Conservation and Management of Archaeological Sites*, Volume 1 (1995): 5-24;

Frank Matero and Elizabeth Moss, "Temporary site protection for earthen walls and murals at Catalhoyuk, Turkey," *Conservation and Management of Archaeological Sites*, Volume 6 (2004): 213-227,

<https://www.tandfonline.com/doi/abs/10.1179/135050304793137694>;

Amila Ferron, "The Consolidation of Earthen Surface Finishes: A Study of Disaggregating Plasters at Mesa Verde National Park," (Master's Thesis, University of Pennsylvania, 2007), 1-158, https://repository.upenn.edu/hp_theses/74/.

for historic earthen structures.⁷⁶ Research regarding stabilizers used in contemporary building construction suggests that more than one additive is necessary to improve water resistance. This research also included testing of different fibers and sands to strengthen and enhance the impermeability of earthen plasters.⁷⁷ Traditional stabilizers (such as plant fibers, etc.) are noted as a method of enhancing adobe bricks and rammed earth's resistance to moisture.⁷⁸ Yet, questions remain as to whether admixtures such as finely chopped hay or other stabilizers could be used to strengthen a shelter coat on archaeological adobe. Research on fibers in shelter coat formulations would require significant additional testing of the fibers themselves and the formulations. Ultimately shared knowledge and connections with practitioners in new earthen construction is important for earthen conservation both in research and practice to determine applicability of approaches to shelter coating on archaeological adobe.⁷⁹ The lack of research and testing of shelter coating as a distinct preventive conservation method suggests a significant gap in existing efforts to conserve earthen heritage.

⁷⁶ Matthieu Pedernana, and Soofia Tahira Elias-Ozkan, 2016, "Impact of local additives on properties of earthen plasters," In *Terra Lyon 2016 Proceedings of the 12th World Congress on Earthen Architecture, Lyon, France, July 11-14, 2016*. Lyon, France: CRAterre, 1-10, https://craterre.hypotheses.org/files/2018/05/TERRA-2016_Th-4_Art-396_Pedernana.pdf;

Matthieu Pedernana and Soofia Tahira Elias-Ozkan, "Impact of various sands and fibres on the physical and mechanical properties of earth mortars for plasters and render," *Journal of Construction and Building Materials*, Volume 308 (2021): 1-21, <https://doi.org/10.1016/j.conbuildmat.2021.125013>;

Tania Santos, Paulina Faria and Vitor Silva, "Can an earth plaster be efficient when applied on different masonries?" *Journal of Building Engineering*, Volume 23, May 2019: 314-323, <https://doi.org/10.1016/j.job.2019.02.011>.

⁷⁷ Pedernana and Elias-Ozkan, "Impact of local additives on properties of earthen plasters," 1-10; Pedernana and Elias-Ozkan, "Impact of various sands and fibres on the physical and mechanical properties of earth mortars for plasters and render," 1-21.

⁷⁸ Correia, Guerrero and Crosby, 224-256;

McHenry, 1-125;

Austin, "Adobe and related building materials in New Mexico," 417-423.

⁷⁹ Avrami, et al., 1-174.

Section 5: Treatment History of Protective Finishes Used at FOUN: 1956-Present

The history of preservation policies and methods employed at Fort Union National Monument since its creation as a national monument is a critical part of evaluating the practice of shelter coating at the site. Adobe deterioration and its repair has been an ongoing practice at Fort Union, even while the fort was in use.⁸⁰ An inspection report from 1886 reported that the plaster originally protecting the adobe buildings had fallen off leaving the walls exposed to the elements, a fact supported by historic photographs during the fort's occupation.⁸¹



Figure 13: Shelter coated adobe at FOUN 2021 (Photo by author).

⁸⁰ Pitcaithley and Greene, *Historic Structure Report, Historical Data Section, The Third Fort Union, 1863-1891*, 15.

⁸¹ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 10.



Figure 14: Exposed Adobe at Fort Union 1954 (Wilson).⁸²

The last assessment and evaluation of protective surface treatments at Fort Union was completed in 1996.⁸³ Records of treatments after 1996 to present exist sporadically in FOUN facilities reports thereby creating a gap in the treatment history. Creating an organized timeline of these treatments, particularly the later methods (amendments and mixes) used for mud shelter coats, will assist FOUN as they assess and adjust their current conservation practices.

This section will examine the history of surface treatments at Fort Union National Monument as a preventive conservation method for the existing adobe walls. FOUN has employed a variety of surface treatments over the years with varying degrees of failure,

⁸² Wilson, *Fort Union National Monument Ruins*.

⁸³ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 1-108.

before the current iteration of using compatible earthen materials in the form of shelter coats. To date, there is no published research of a comprehensive treatment history at an earthen heritage site that includes an examination of the contemporary practices of shelter coating as a preventive conservation method. Louise Cooke's 2010 publication addresses shelter coating as a method amongst a variety of other preventive conservation strategies employed at several earthen heritage sites around the world. Other strategies include backfilling, sheltering, consolidation, encapsulation, reconstruction and restoration, removal or relocation, or "do nothing."⁸⁴ A review and analysis of the treatment history as it pertains to the adobe walls at Fort Union will assist the park in making decisions regarding current and future preventative conservation approaches based on scientific research.

Surface Treatments with Synthetic Resin Coatings

Since 1956, numerous surface stabilization treatments have been made to protect the remaining adobe walls at the site, including various commercial and custom synthetic resin waterproofing compounds that were sprayed directly onto the adobe surface until unamended shelter coats came into use in 1981.⁸⁵ There is significant documentation of surface treatments employed to conserve the adobe walls at Fort Union National Monument from 1956 to the present.⁸⁶ The Fort Union stabilization reports volumes 1-3 from 1956-1960 detail room by room stabilization efforts carried out, including the use

⁸⁴ Cooke, 1-160.

⁸⁵ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 1-108.

⁸⁶ Richert, and Vivian, *Ruins Stabilization in the Southwestern United States*, 1-139; Zhu, 1-164;

Kimmel and Matero, "An Outline History of Stabilization and Conservation Treatments: Fort Union National Monument," 1-61; Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 1-186; Hartzler and Oliver, "Learning from the Site: Evolution of the Fort Union Strategic Preservation Plan," 39-45.

of cement stabilized adobes and mortars and waterproofing chemicals in the form of types of synthetic resins sprayed on the surfaces of adobe and plaster.⁸⁷ In 2021, interviews with National Park Service (NPS) staff revealed that current shelter coat formulas are not easily applied to soil-cement adobes or to the original adobes that may still have residue from these early treatments.⁸⁸ The rehabilitation reports provide useful information about the original treatments used at the site that may still have lasting impact today. Richert and Vivian's 1974 report on *Ruins Stabilization in the Southwest* details causal factors of deterioration in adobe and presents the range of treatments employed at NPS sites including those at Fort Union.

The Kimmel and Matero manuscript from 1995 attempted to create the first detailed outline of the chemical treatments used historically in situ. Their report showcases the evolution of treatments, from the use of silicone-based resins in the 1950s, epoxy resins in the 1960s, and notes the issues with each treatment that were not known or not noted at the time of their use. General observations about silicones and epoxies are provided in the report based on historic accounts throughout testing of treatments. Epoxy resins and silicones were previously applied directly to a dry or wetted adobe wall surface, with no additional layer applied.⁸⁹ Later, unamended 'mud' shelter coats were attempted with little visual or performance success. This section reviews each of the chemical treatments implemented at Fort Union and extends the treatment history by compiling information from existing technical data sheets and conducting research about chemical families and the physical properties they impart.

⁸⁷ Rex Wilson, *Final Report: Rehabilitation of Historic Structures Volumes I-III Fort Union National Monument* (Santa Fe, NM: U.S. Department of the Interior, National Park Service, 1956-1960).

⁸⁸ Fort Union National Monument Site Visit and Tour, Recorded by Alison Cavicchio, *University of Pennsylvania*, October 11, 2021.

⁸⁹ Kimmel and Matero, 1-61.

Mixes and Application Methods of Shelter Coats

Earthen shelter coat formulations applied directly to the original adobe walls came into use in 1981 at Fort Union and have evolved since that time.⁹⁰ In 1981 Fort Union abandoned soil cement caps and silicone water repellent treatments and began using traditional materials, namely unamended clay-rich soils, for both capping and shelter coating.⁹¹ Literature on shelter coat formulas from 2000-2009 is not available at the NPS administrative office at Fort Union, yet the office has maintained extensive records of the shelter coat mixes applied to the adobe walls from 2010-2018. This includes detailed information on the unamended and amended shelter coat layers, including the 2018 formula that is still in use today employing two different soils based on color. Surface treatments have been tested and published in the past yet shelter coat practices remain largely unstudied.

In 1996 the Preservation Action Plan for Fort Union reviewed maintenance materials and conservation methods carried out from 1956-1996 and noted that there was still a high rate of material loss despite the continuous conservation efforts.⁹² Since 1996, no further testing of surface treatments has been conducted at the site and localized material failure is evident in cracked adobe bricks and loss behind spalled shelter coats. To protect the adobe walls, treatments from 1996 to present need to be documented and evaluated to inform how these treatments have performed and more importantly how they have affected the adobe walls beneath.

⁹⁰ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 1-186.

⁹¹ *Ibid.*

⁹² Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 161; Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 1-108.

The 1996 Preservation Plan notes that “effective management of the cultural resources at Fort Union now and in the future will ultimately depend on new knowledge about the rate and complexity of the deterioration (or change) of the ruins and those factors or variables which have in the past and will continue in the future to affect the ruins.”⁹³ A history of deterioration and treatment was designated as an important part of a coordinated study designed to address this objective. Documentation of treatments is invaluable as it forms a record that can be used to identify problems and evaluate effectiveness, and “ultimately arrive at better treatment solutions.” The history of preservation at the site sought to include past and present conservation treatments and maintenance practices prepared from park documents and field observations of recorded treatments.⁹⁴

This analysis updates the treatment history to the present day to provide a comprehensive record of historical surface treatments and current shelter coating practices employed at the site to date. Past surface treatments at Fort Union have included use of the following: Daracone™, Dehydratine™ 22, DC 129G, DC 770, Hydrocide SX Colorless™, Hydrocide Colorless 101™, Klear-Film, Methyl methacrylate and 2% ethylene glycol dimethacrylate, Pencapsula™, Polystyrene, Sandstone and Adobe Coating™ (dissolved in paint thinner, xylenes or kerosene), Sileaneal™/DC 772, Silexore™, and other unspecified preservatives including a silicone solution.⁹⁵ In some years, multiple chemicals were used on different buildings and walls throughout the site. In 1996 Oliver and Hartzler’s preservation plan noted that “maintenance materials

⁹³ *Ibid.*

⁹⁴ *Ibid.*

⁹⁵ Kimmel and Matero, 41.

applied in the past were wall caps and shelter coats of soil cement, which were periodically sprayed with water repellent silicones.” Soil cement shelter coating was used at the site as a method of stabilization for wall capping and filling gaps in mortar or bricks.⁹⁶ Soil cement adobes continued to be used at the site to patch repair walls until 1996. Many of the surface treatments used historically were intended to be long term fixes to the problem of protecting the adobe walls from surface erosion, yet they failed because of compatibility issues with the adobe and in some cases the creation of an impervious layer which restricted the natural flow of moisture through the walls. A shelter coat, used currently, is intended to be a sacrificial treatment method that is compatible with the original wall system and is meant to be replaced upon failure from weather events.

The 1995 treatment history and the 1996 Preservation Action Plan for FOUN form the basis upon which the extended treatment history will be laid out. The chronology of these historical treatments is as follows, organized by five major phases. Each phase saw the use of various and newly developed synthetic resins including silicones, epoxies, polyvinyl acetate and acrylic emulsions, and in part reflect their wider use in the construction industry (Figure 15).

⁹⁶ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 1-108.

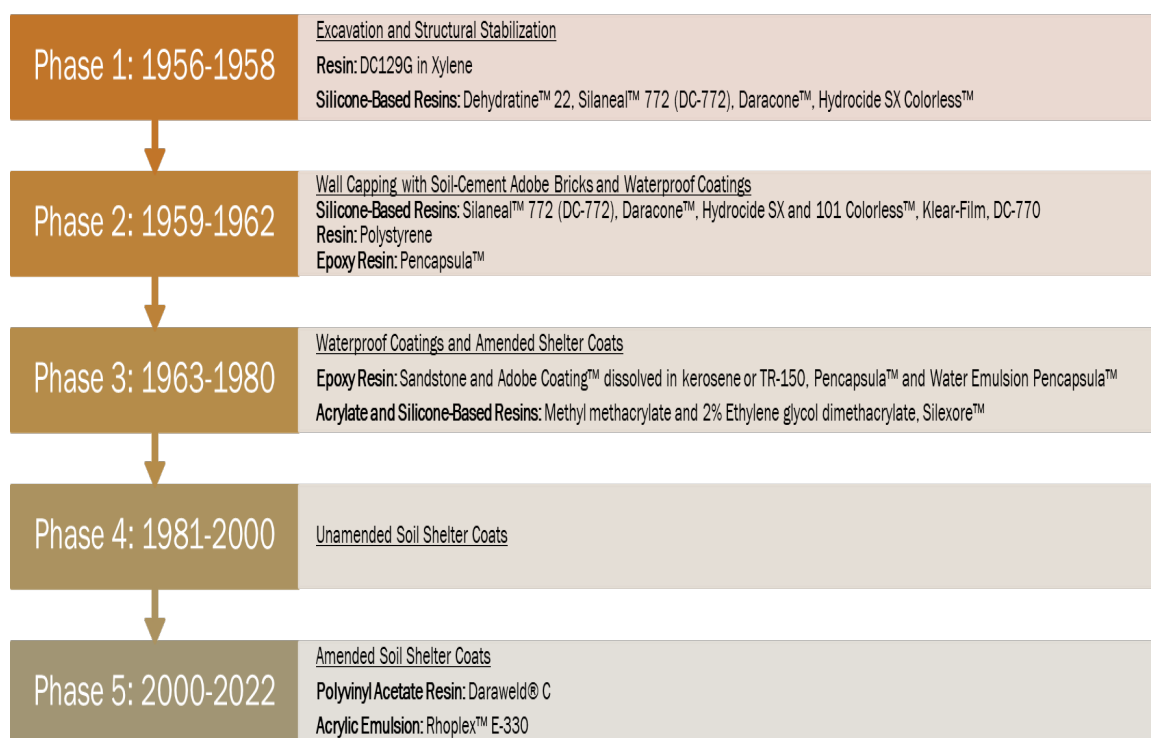


Figure 15: Fort Union Treatment history by phases (Graphic by author).

Phase 1: 1956-1958, Excavation and Structural Stabilization

- 1956 – 1960: Silaneal™ 772 (DC-772) solution was sprayed onto the walls (1:9 DC-772:water).
- December 1957: Daracone™ was sprayed onto the chimneys, Hydrocide SX™ was brush applied, and DC 129G dissolved in an unspecified amount of Xylene was sprayed onto walls.
- October 1958: Daracone™ mix was applied with a power sprayer, Dehydratine™ 22 sprayed onto the walls.
- November 1958: Unspecified silicone solution and DC 129G sprayed onto walls.
- October 1958 - July 1959: Silaneal™ 772 solution sprayed onto walls (1:9 Silaneal™: water).

Overview of products used during this period by chemical family and class:

Synthetic Resins:

- **DC 129G:** DC 129G was formulated as a masonry water repellent in the mid-1950s by Dow Corning. It was an experimental product with a low molecular weight of which no performance was recorded.⁹⁷ Documentation of the product continues to be almost non-existent to this day. Its low molecular weight suggests that it was being tested as a product that would not impart heat sealing properties onto the substrate. Xylene, an organic solvent, was used to dissolve the resin. Resins are introduced into porous materials such as soil by dissolving the resin in a solvent like Xylene.⁹⁸ DC129G is a thermoplastic resin, a polymer in which the monomers are linked together to form two-dimensional linear chains that are soluble in many solvents.⁹⁹
- **Silicones:** Dehydratine™ 22, Silaneal™ 772 (DC-772), Daracone™, Hydrocide Colorless SX™
- **Dehydratine™ 22:** Developed by Tamms Industries, formerly Horn Corporation, Dehydratine™ 22 is a 3% silicone resin dissolved in an unspecified solvent. The product was developed in conjunction with the product Daracone™ by Dow Corning and is identical in composition to Daracone™ aside from their varied silicone percentages.¹⁰⁰ Specifications provided by Tamms included directions to flood the precleaned masonry surface using a low-pressure spray unit or brush. It was noted that at the time of use Dehydratine™ 22 was a silicone water repellent used as a

⁹⁷ Kimmel and Matero, 1-61.

⁹⁸ J.O. Tate, N.H. Tennent, and J.H. Townsend, eds., 1982, "Resins in Conservation," In *Proceedings of the Symposium on Resins in Conservation, Edinburgh, UK, May 21-22, 1982*, Edinburgh, UK: Scottish Society for Conservation and Restoration.

⁹⁹ Donny L. Hamilton, "Adhesives and Consolidants." In *Methods for Conserving Archaeological Material from Underwater Sites* (College Station, TX: Center for Maritime Archaeology and Conservation, Texas A&M University, 1999), 11-14, <https://nautarch.tamu.edu/CRL/conservationmanual/File2.htm>.

¹⁰⁰ Kimmel and Matero, 27.

generic water proofer with little regard for its unique properties.¹⁰¹ Information about Dehydratine™ 22 is not available through Tamms Industries today, yet the company is described as a leading manufacturer of high-performance products for the concrete construction industry.¹⁰² The Tamms technical data sheet for Dehydratine™ 4, 6 and 10, described as a damp proofing agent for masonry, notes that the product may require a petroleum based- paint thinner or stronger solvent to remove it, suggesting that a similar solvent was used to apply the resin.¹⁰³ Based on the TDS for other Dehydratine™ products, and since Daracone™ required a kerosene or non-water-based solvent, Dehydratine™ 22 likely required the same type of solvent.

- **Silaneal™ 772 (DC-772):** Manufactured by Dow Corning®, Silaneal™ or DC-772 is a water-based silicone resin (sodium methyl siliconate) that has been in production since 1962 and is described as a water repellent for masonry surfaces that is designed to impart water repellency and reduce water absorption of a variety of substrates.¹⁰⁴ Silaneal 772 was tested at Fort Union in an effort to find a silicone-based resin that was less expensive than Daracone, discussed below.¹⁰⁵ Specifications during its use at Fort Union during this phase indicated that it was to be mixed with water and spray applied to a precleaned surface at a recommended outdoor temperature of 70 degrees Fahrenheit. At Fort Union the walls were sprayed from the top to allow for run-down until the walls absorbed all the product that they could retain. During its use it was

¹⁰¹ *Ibid.*, 28.

¹⁰² “Tamms,” Python Corporation, <https://www.pythoncorp.com/content/page/tamms>.

¹⁰³ DEHYDRATINE® 4, 6, and 10. Technical Data Sheet. Tamms Industries. 2000. https://dpproducts.com/old_site/products/tamms/dehy4610.pdf.

¹⁰⁴ Dow Corning® 772 Water Repellent. Dow Corning Product Information Water Repellent. Dow Corning®. 2002. <https://environex.net.au/wp-content/uploads/2016/04/Dow-Corning-772.pdf>.

¹⁰⁵ Roland Richert and Gordon Vivian, “Appendix I Accelerated Weathering Tests” In *Ruins Stabilization in the Southwestern United States* (Washington, DC: U.S. Department of the Interior, National Park Service, 1974), https://www.nps.gov/parkhistory/online_books/archeology/10/contents.htm.

observed that when DC-772 dried it produced a thin water repellent film which was easily punctured by hail and sandstorms. DC-772 was impervious to further application of the same product once dry but was not resistant to products that used non-water-based solvents such as Daracone™ or DC-770.¹⁰⁶

Current product data on waterproofing agents from Dow Corning® lists the benefits of DC-772 as a water-dilutable solution providing water repellency on a variety of substrates, including bricks and ceramics.¹⁰⁷ Silicones are made up of long chain linked polymers which have weak secondary bonds, giving them the flexibility of a thermoplastic upon temperature changes.¹⁰⁸ In theory, DC-772's physical properties allow it to penetrate the substrate and provide a protective water repellent layer with the ability to allow water vapor to pass, though no testing is listed as being conducted for use on unfired brick.¹⁰⁹

- **Daracone™:** Daracone™ is a 5% hydrocarbon-based silicone¹¹⁰, manufactured by Dewey and Almy Chemical Company formerly based in Cambridge, Massachusetts. Trademark for the product is currently expired, having last been filed in 1996 for use as a masonry water repellent.¹¹¹ The chemical formula for the product is unknown, though Kimmel and Matero surmised that it was dissolved in a non-water-based solvent (kerosene was commonly used in this area as a solvent for silicones) and brush applied to the substrate. During its use at Fort Union, it did not form an impervious surface crust on the adobe walls thereby allowing water to penetrate the

¹⁰⁶ Kimmel and Matero, 39.

¹⁰⁷ Dow Corning® 772 Water Repellent.

¹⁰⁸ Helen Wilks, ed., *Science for Conservators, Volume 3: Adhesives and Coatings* (New York, NY: Museums and Galleries Commission, Routledge, 1992), 1-55.

¹⁰⁹ Water Repellent Selection Guide. Dow Corning® brand Construction Chemicals. Dow Corning®. 2004. <https://www.gluespec.com/Materials/SpecSheet/1ccf19ae-f259-40d5-ba00-3431ec03219a>.

¹¹⁰ Richert and Vivian, *Ruins Stabilization in the Southwestern United States*, 1-139.

¹¹¹ "DARACONE- Trademark Details," Justia, <https://trademarks.justia.com/716/60/daracone-71660786.html>.

- coating and contribute to erosion. None of the silicones tested at Fort Union were able to combat this problem. It was described for use as “Daracone™ or equivalent,” thereby implying that Daracone™ was considered a generic waterproofing agent “with little attention given to differences in silicone performance.”¹¹² Matero and Kimmel note that following the use of Daracone™, silicones were used as a secondary treatment at Fort Union as epoxy resins became favored by new administrative staff as they were thought to repel intra porous moisture.
- **Hydrocide SX Colorless™:** Manufactured by L. Sonneborn Sons, Inc., Hydrocide SX Colorless™ is a 5% silicone resin for use as a masonry water repellent. The product used mineral spirits as the solvent and claimed to have water and freeze-thaw resistance when spray or brush applied. Claims that the product could minimize weathering were disputed by AIA’s *Building Products Register* stating that it was not meant to improve weathering resistance and was not recommended for use on limestone or iron spot brick.¹¹³ A court case from 1934 involving L. Sonneborn Sons, Inc. noted that Hydrocide Colorless™ was to be brush applied upon application.¹¹⁴ No current product information was available at the time of report writing.

Phase 2: 1959-1962, Wall Capping with Soil-Cement Adobe Bricks

- January and May 1959: Unspecified silicone-based resins used, as well as the synthetic resins Daracone™ and Silaneal™ 772 (DC-772) sprayed onto walls and capping.

¹¹² Kimmel and Matero, 26.

¹¹³ *Ibid.*, 31.

¹¹⁴ *Genesee C.P. Fire Relief Assn. v. Sonneborn Sons*, 1934. 263 N.Y. 463, 189 N.E. 551, <https://casetext.com/case/genesee-cp-fire-relief-assn-v-sonneborn-sons/>.

- July-December 1959: Experimental Adobe wall testing (see below)
- April and June 1960: Silaneal™ 772, Dehydratine™ 22
- August 1960: Silaneal™ 772
- September 1962: Mud diluted with 1:5 Pencapsula™:mineral spirits or clear fuel oil as a crack filler, patching or mortar repair. Sprayed onto adobe walls.

Experimental Adobe Wall Tests at Fort Union

- July 1959: Silaneal™ 772, Klear-Film™ applied to different sections of the test walls
- August-September 1959: Silaneal™ 772, Daracone™, DC-770, Hydrocide SX Colorless™, Hydrocide Colorless 101™, Polystyrene applied to different sections.
- November 1959: Daracone™ and Silaneal 772™.

Overview of products used during this period by chemical family and class:

Synthetic Resins

- **Silicone Resins:** Silaneal 772™ (DC-772), Daracone™, Hydrocide SX Colorless™, Klear-Film, DC-770, Hydrocide Colorless 101™
- **Klear-Film:** As silicone resin testing continued at Fort Union, Klear-Film was tested at the site. This silicone product was applied with a brush to tests walls to provide water repellency to the substrate.¹¹⁵ Product information outside of that provided in the 1995 report is nonexistent.
- **DC-770:** This product is another silicone resin (monomethyl dimethyl silconate) manufactured by Dow Corning for use as a water repellent. It was designed to be mixed with a non-water-based solvent such as mineral spirits.¹¹⁶ Updated product

¹¹⁵ Kimmel and Matero, 33.

¹¹⁶ *Ibid.*, 30.

information is not available from Dow Corning or other sources, suggesting that the product is no longer manufactured.

- **Hydrocide Colorless 101™:** Hydrocide Colorless 101™ is a liquid silicone water repellent manufactured by L. Sonneborn Sons, Inc. for use on “limestones and natural stones used as structural veneers.” It was noted that the product may leave white surface deposits. The application of the product temporarily bleached the wall at FOUN after it was brush applied and disintegrated after a normal level of rainfall.¹¹⁷ Updated product information is not available from Sonneborn or other sources, suggesting that the product is no longer manufactured.
- **Polystyrene:** Polystyrene was developed by Dow Chemical and is a styrene derivative, created from polymerized styrene plastic.¹¹⁸ The product was used once at Fort Union, at 15% by volume polystyrene dissolved in benzol and applied directly onto the test wall over a coating of Silaneal™ 772. It ultimately caused the wall to darken and turn a yellowish color, after which it broke down completely following rainfall.¹¹⁹ A polymerized plastic is polyaddition resin and acts as a thermoset, meaning that the product becomes rigid and hard upon curing.¹²⁰

Epoxy Resins: Pencapsula™

- **Pencapsula™:** Pencapsula™ was manufactured by the Texas Refinery Corporation specifically for use at archaeological sites in New Mexico and Arizona. It is an oil-modified polyurethane meant to be mixed with petroleum-based solvents such as

¹¹⁷ *Ibid.*, 31.

¹¹⁸ *Ibid.*, 37.

¹¹⁹ Kimmel and Matero, 37.

¹²⁰ “Modern technology of synthetic resins and their applications,” Ajjay Kumar Gupta, Niir Project Consultancy Services, June 4, 2020. <https://www.linkedin.com/pulse/modern-technology-synthetic-resins-applications-2nd-revised-gupta/>; Wilks, ed., *Science for Conservators, Volume 3: Adhesives and Coatings*, 25.

TRC-150, paint thinner, kerosene and clear oil fuel, and sprayed onto the walls using a high-pressure sprayer at maximum psi. Initially hailed as the answer to weathering adobe, it ultimately was found to cause more damage than protection. No information about TRC-150 is currently available, yet at the time of its use it was noted that kerosene and fuel-based solvents did not provide reliable color matches or good adhesion. FOUN staff found that Pencapsula™ did not produce the same strength improvements in adobes that soil-cement could.¹²¹ While silicones were used for surface protection from weathering and were secondary in importance to structural stabilization, epoxy resins such as Pencapsula™ were used in stabilization efforts for the walls.¹²²

Pencapsula™ is a polycondensate epoxy resin and acts as a thermoset, forming a rigid cross-linked bond.¹²³ Epoxy resins are network polymers that act as adhesive, thermosetting plastics when the hardening agent is added to the epoxy, creating cross-linked chains that impart “exceptional toughness, adhesion, and chemical resistance.” The solvent composition used with epoxy resins is critical as it directly affects the interaction of the resin with the surface of the substrate. Mineral spirits are noted to have no effect on epoxy reactions and rather behave as dilutants.¹²⁴ Kerosene as a solvent appears to have been incompatible with the resin and surface of the adobe.

¹²¹ Kimmel and Matero, 34.

¹²² *Ibid.*

¹²³ Hamilton, “Adhesives and Consolidants,” 12.

¹²⁴ Charles Selwitz, *Epoxy Resins in Stone Conservation* (Los Angeles, California: J. Paul Getty Trust: The Getty Conservation Institute, 1992), <https://www.getty.edu/publications/virtuallibrary/0892362383.html>.

Phase 3: 1963-1980, Soil-Cement Shelter Coats

- November 1963: Sandstone and Adobe Coating™ with TRC-150 solvent, and Silexore™ was also used on a separate wall, Pencapsula™ also applied separately as indicated in 1962. Silexore™ was manufactured by J.W. Rylands Co. and was defined as a protective coating for concrete by the Michigan State Highway Department in 1964.¹²⁵ A 1935 edition of *The Architects' Journal* provided trade notes on Silexore™, indicating that it was a flat paint made from a silicate liquid and a zinc-based powder that were mixed. The silicate liquid was delivered separately and could be used in the pure liquid form as a colorless water proofer to form a vapor porous, waterproof membrane on the surface to which it was applied. It could be brush or spray applied, and its application solidified loose and friable surfaces.¹²⁶
- December 1964: Sandstone and Adobe Coating™ with TRC-150 solvent
- August 1966: Pencapsula™
- 1967: 1:4 Pencapsula™: mineral spirits
- 1971: No specific information available
- 1972: Soil cement capping and patching, followed by spraying of Silaneal 772™ to the walls.
- 1973-1977: Treatment information is limited. Superintendents' reports note that walls were treated "presumably by the methods recommended in 1972."¹²⁷

¹²⁵ M.G. Brown, *Summary of Laboratory Evaluation of "Silexore" Protective Coatings for Concrete. Research Project R-63 NM-101. Research Report No. R-479* (Michigan: State Highway Department, October 19, 1964).

¹²⁶ Trade Notes: Paint for Concrete. F.R.S. Yorke. July 1935; 82. *The Architects' Journal*.

<https://proxy.library.upenn.edu/login?url=https://www.proquest.com/trade-journals/trade-notes/docview/1542742667/se-2?accountid=14707>.

¹²⁷ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 17.

- 1978: Methyl methacrylate and 2% Ethylene glycol dimethacrylate applied with watering cans directly to the walls before repointing.¹²⁸
- 1979: No preservation information recorded.¹²⁹
- 1980: Hartzler and Oliver presumed that the treatment this year were those recommended in 1972 and no other information has been uncovered to date.

Overview of products used during this period by chemical family and class:

Synthetic Resins

- **Epoxy Resins:** Sandstone and Adobe Coating dissolved in kerosene or TR-150, Pencapsula™ and Water Emulsion Pencapsula™
- **Pencapsula™:** In 1962, the epoxy resin Pencapsula™ was used for waterproofing the walls at Fort Union by spraying it directly onto the adobes. In 1975 the park recorded that Pencapsula™ was having a negative impact on the walls, causing an impervious layer which would then spall off upon weathering, taking the original adobe wall with it.¹³⁰
- **Sandstone and Adobe Coating™:** Texas Refinery Corporation also developed this product as a precursor to Pencapsula™ that could be used with two different solvents: TRC-150 and kerosene. Fuel based solvents were used at the time over water-based solvents to decrease costs. Ultimately the use of this epoxy resin resulted in an imperfect coating that retained moisture behind coated patches.¹³¹
- **Water Emulsion Pencapsula™:** Designed as an experimental product by Texas Refinery Corporation, the product was tested during phase three for use in mortar

¹²⁸ Kimmel and Matero, 4.

¹²⁹ Hartzler and Oliver, *Fort Union Preservation Action Plan: Research and Development Project Final Report*, 19.

¹³⁰ Kimmel and Matero, 35.

¹³¹ *Ibid.*, 36.

repointing. It was found to be durable, yet no further purchases of the product were recorded. The water emulsified Pencapsula™ cost the same as regular Pencapsula™ yet it provided less per volume. As such it may have simply been discontinued due to cost.¹³²

- **Silicone-based resins:** Methyl methacrylate and 2% Ethylene glycol dimethacrylate
- **Methyl methacrylate and 2% Ethylene glycol dimethacrylate:** No specific manufacturing information is available. The product was applied with watering cans at Fort Union.¹³³ General research notes that this mixture creates a polymer with a structure like silicone.¹³⁴ This suggests the product is a silicone-based polycondensate resin, behaving as a thermoset. Silane treatments used in conservation are typically irreversible.¹³⁵

Phase 4: 1981-2000, Unamended Soil Shelter Coats

- 1981-1995: In 1981 Fort Union staff began using more materially compatible shelter coats of unamended soil. The Park had planned to treat the walls every five years, yet the ephemeral nature of the coats required reapplication as often as once a year. Soil for shelter coats was procured from Las Vegas or Tecolote, New Mexico, and sand was procured from Las Vegas, NM. These materials were used until August 1995.¹³⁶

¹³² *Ibid.*

¹³³ *Ibid.*, 15.

¹³⁴ Ulku Ramelow and Sreedhar Pingili, "Synthesis of Ethylene Glycol Dimethacrylate-Methyl Methacrylate Copolymers, Determination of their Reactivity Ratios, and a Study of Dopant and Temperature Effects on their Conductivities," *Polymers, Volume 2, No. 3*: (2010) 265-285, <https://doi.org/10.3390/polym2030265>.

¹³⁵ C.V. Horie, *Materials for Conservation: Organic consolidants, adhesives and coatings* (Cornwall, UK: Butterworth & Co. Ltd., 1987).

¹³⁶ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 30.

Fort Union's administrative history notes the years 1980 to 1991 as the "age of improvement."¹³⁷

- 1988: Maintenance using before and after photos of shelter coating describing the work being done begins, later shifting to be called "ruins stabilization monitoring forms" and ruins stabilization inspection forms (1991 and 1992).
- 1993: Straw was added to the unamended adobe blocks and mud shelter coats to strengthen the mixture.
- 1994: Masonry cement added to the shelter coat mix.
- 1995: Undocumented experiment conducted to apply an unamended mud shelter coat layer, then cover it with a protective layer of the same mixture plus a one pound can of El Rey Stucco. At this time the park was dissatisfied with the Tecolote/Las Vegas soil and began to use a 3:1 mixture of Watrous sand and local soil from a nearby arroyo where debris from the excavation of the ruins had been deposited.¹³⁸
- 1996: Test wall implementation at Fort Union.
- 1997-2000: Test wall implementation evaluated the performance of soil-cement, Type S lime modified soil, acrylic amended, and unmodified soil.

Hartzler and Oliver's report covering up to 1995 notes that the northwest facing walls were at greatest risk and most often required retreatment. From 1989-1991 they were 73% of the total retreated walls in a season, and 12% of those northwest walls had to be treated a second or third time. Given the ephemeral nature of the adobe, in 1996 the report noted that the staff were not able to keep up with the cycle of shelter coating

¹³⁷ Zhu, 31.

¹³⁸ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 32.

treatment which was to be conducted on a four-to-five-year rotation. This was due to two major factors: inadequate maintenance materials and procedures, including the unamended soil shelter coats which were destroyed by weather in as little as a day, and the lack of funds to hire more workers to carry out the maintenance or additional research on effective preservation methods.¹³⁹ Their report indicated that while the method of unamended soil shelter coats was the least intrusive of all the treatments to that point, it was inadequate in meeting the demands of the site and the limitations of funding.¹⁴⁰

The 1996 implementation phase of the Preservation Action Plan conducted surface treatment experiments on test walls at Fort Union to evaluate the performance of soil-cement, Type S lime modified soil, acrylic amended, and unmodified soil. The research also included an earthen material characterization component. Ultimately this research demonstrated that soil-cement adobes are very durable when exposed to water, yet they have poor water absorption ability. Type S lime and acrylic emulsion (El Rey Superior 200) both had greater absorption rates than the cement and hydraulic lime. The tests noted that the “characteristics of a preferred capping material would include high water absorption...and high-water vapor transmission.” The authors argued for testing over a period of at least ten years for both the historic and adobe test walls.¹⁴¹ Rhoplex™ E-330 and other acrylic emulsions have been used at Fort Union since this testing was conducted, although the test walls have long since disappeared. Since the 1996 Preservation Action Plan and implementation project was completed there have been no

¹³⁹ *Ibid.*

¹⁴⁰ *Ibid.*

¹⁴¹ *Ibid.*, 100.

further studies to document and analyze the surface treatments for the adobe walls at Fort Union.

In the early 1980s an adobe test wall project was undertaken in two phases over the course of fifteen years at Fort Selden State Monument in Radium Springs, New Mexico. A review of the tests was published in 2000, analyzing the project's experimentation with six different protective coatings to evaluate the performance of various concentrations of additives including organic additives such as linseed and grapeseed oil, and synthetic resins including El Rey Superior Additive 200, El Rey Adobe Protector (a water repellent), and Rhoplex™ E-330. Organic additives such as linseed oil were found to perform as poorly as unamended soils. The analysis indicated that although Rhoplex™ E330 had been recommended in earlier tests, El Rey Superior 200 displayed the best overall performance for earthen shelter coats in terms of erosion resistance. Lower concentrations of synthetic resins mixed with earthen shelter coats (called renders by the author) provided the greatest protection to adobe walls, yet the report called for laboratory testing to be conducted in addition to these field tests to pinpoint why certain products were successful or why they failed. The report notes that soil properties are particularly critical when using an acrylic emulsion such as Rhoplex™ or El Rey Superior given that the soil is what imparts properties to the acrylic.¹⁴² Overview of products recommended during this period by chemical family and class (from Fort Selden tests):

Synthetic Resins

- **Acrylic Emulsions:** El Rey Superior 200 and Rhoplex™ E-330

¹⁴² Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 78.

- **El Rey Superior 200** (Contemporary product name: Parex USA Adacryl Acrylic Admix & Bonder): A acrylic polymer emulsion additive designed for use with Portland cement stucco bases. Promotes hydration and curing of stucco bases, improves bonds between stucco bases and dense masonry surfaces.¹⁴³ It was used on test walls only at Fort Union.
- **Rhoplex™ E-330**: See phase five.

Phase 5: 2000-Present Amended Soil Shelter Coats

The practice of shelter coating was established in 1981 and continues to this day using a modified formula applied once a year. As mentioned previously, literature on shelter coat formulas used from 2000-2009 is not available at the Fort Union administrative office, yet FOUN has maintained extensive records of the shelter coat mixes applied to the adobe walls from 2010 to present. The 2010 field report notes that Daraweld® C, a polyvinylacetate resin, was being phased out in favor of Rhoplex™ E-330. Daraweld® C or similar chemicals may have been used prior to 2010 given that Daraweld® C had been previously used for surface treatment of adobe at Fort Selden, where it was noted that its use had “diminished due to problems caused by its relative impermeability.”¹⁴⁴

Rhoplex™ E-330 has been in use in the Southwestern United States since 1973. In testing at Chaco Canyon in 1975 Rhoplex™ E-330 was the most successful of the polymer emulsions used for adobe bricks, mortars, capping. Recommendations suggested

¹⁴³ Adacryl Admix & Bonder. PAREXUSA Product Data Sheet. 2014. https://www.parex.com/docs/librariesprovider5/additional-product-literature/product-data-sheets-msds/adacryl-admix-bonder.pdf?Status=Master&sfvrsn=7d965a0e_8.

¹⁴⁴ Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 30.

that Rhoplex™ E-330 should be mixed so that it contains approximately 13% chemical solids by weight (1 Rhoplex™ E-330 to 2.5 water), and the soil used should be approximately 70% sand, 20% clay, and 10% or less silt. Word spread across the southwest about this product yet the original recommendations for its optimal use in sandy soils have not always been followed.¹⁴⁵

Since 2010 Rhoplex™ E-330, an acrylic polymer resin emulsion, has been used to treat the second layer of shelter coating at Fort Union with different ratios of soil to sand and Rhoplex™ tested in situ each year. The current practice of shelter coating consists of a two-coat system of an unamended layer followed by an amended layer modified with Rhoplex™ E-330. This system is based on the idea that the unamended layer will isolate and restrict any damage to the original adobe from the amended top layer when it fails. The first layer consists of a ratio of three soil to one sand (by volume) mixed with water to create an unamended shelter coat (called mud plaster by Fort Union). The second layer, called a topcoat mud plaster mix, consists of the unamended soil to sand mixture, plus one-part Rhoplex™ E-330 to seven parts water to create a 14% Rhoplex™ E-330 solution. The soil:sand mixture and the Rhoplex™:water solution are mixed together as nine parts soil/sand to one part Rhoplex™/water solution.

Ratios According to the FOUN Masonry Mix Guidelines
1 Sand : 3 Soil
1 Rhoplex E-330 : 7 Water (creates a 14% solution)
1 Rhoplex solution : 9 Soil/Sand Mix

Table 1: Ratios by volume for shelter coat formulations according to FOUN Masonry mix guidelines as provided by FOUN.

¹⁴⁵ Hartzler, "A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites," 16.

Both layers are applied by hand using rubber gloves. Theoretically shelter coats are meant to be removed before a repair is carried out to address damage after spalling occurs. At Fort Union when a shelter coat spalls it leaves a section of loss where multiple layers are visible. This means that the practice at Fort Union is to remove any loose shelter coat around an area of spall and then patch the spall with new shelter coat layer. It is current practice to coat over the existing shelter coat if numerous areas of spall occur, creating various layers of shelter coating on a wall. The field visit portion of this study was critical to understand current shelter coat mixes and application methods. Shelter coats are applied every season based on a wall prioritization schedule and photo log documentation. The most recent iteration of shelter coating was applied during the current season between May and September 2021. Three types of application methods were identified during the site visit, including coating of the full wall, a section of the wall, or a partial patching job.

Soil from nearby sites determines the hue of the shelter coat. In 2021 a red soil from Tecolote, New Mexico was used for aesthetic purposes based on recommendation from Jeremy Moss, Chief Archaeologist at FOUN and Pecos National Historical Park. As noted previously, Tecolote soil was used at Fort Union from 1981 until 1995 when it was discontinued after NPS staff became dissatisfied with its performance.¹⁴⁶ In 2020 the shelter coat mixture was comprised of a brown soil with a higher volume of aggregate (3:1 ratio of brown soil to sand), while in 2019 the mix was made with a light red soil. At present all three years of shelter coat can be seen on numerous walls throughout the site.

¹⁴⁶ Hartzler and Oliver, *Fort Union Preservation Action Plan: Implementation Phase Project Final Report (Test Walls Program)*, 32.

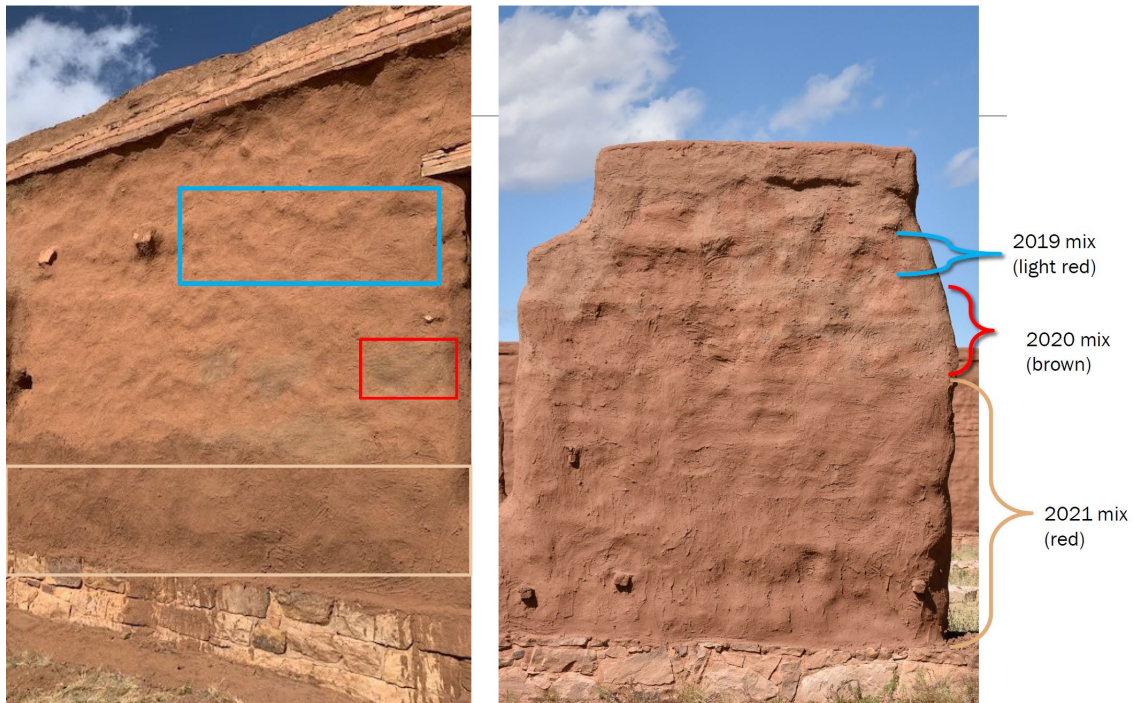


Figure 16: Different soils used for shelter coating at Fort Union (Photos by author).

An analysis of the major shelter coat spalling recorded on site in October 2021 indicates that the formula and application method used at present needs further analysis. Major shelter coat spalling, defined as one foot in width or height, was identified on walls that were shelter coated in September 2021, less than one month prior to observation (Appendix A). The thicknesses of coats ranged from 1/4" to 2", and numerous walls had as many as five layers of shelter coats, including the latest layer from the 2021 season. These observations and interviews with staff on site confirmed that old shelter coats are not being removed prior to the new application, creating an accumulation of shelter coat layers containing Rhoplex™ E-330. FOUN staff do not measure the shelter coat to a certain thickness when applying the coating to the walls, rather the shelter coat is applied liberally and at the discretion of the staff member applying resulting in a variety of thicknesses across the walls. Fort Union experiences strong winds and rain during the

monsoon season (June-September), followed by snow and hail during the winter.

Significant weather events crack the shelter coat and many of these areas display spalling or incipient spalling (partial detachment). At present, shelter coat cracks and spalls are repaired by patching the shelter coat rather than removing the entire coating from the wall and replacing it with a fresh one.



Figure 17: Spalled shelter coat at FOUN exposing multiple layers of shelter coating and underlying adobe (Photo by author).

Overview of products used during this period by chemical family and class:

Synthetic Resins: Daraweld® C

- **Daraweld® C:** Manufactured by GCP Applied Solutions, Daraweld® C is a polyvinyl acetate emulsion, a Polymer & Vinylacetate- dibutylmaleate copolymer dispersion, that acts as a bonding agent for concrete. GCP describes Daraweld® C as an adhesive resin or bonding agent for concrete that complies with the requirements of ASTM C1059 Standard Specification for Latex Agents for Bonding Fresh to Hardened Concrete.¹⁴⁷ GCP notes that the product will improve adhesion to the substrate, and when mixed a proportion of sand should be used. The product sheet also notes that the surface to which the product is applied should be clean.¹⁴⁸

Polyvinylacetate is a polyaddition resin that acts as a thermoplastic and is soluble in several water-based solvents such as acetone and ethanol. Xylene can also be used as a solvent, but the non-toxic water-based solvents are recommended.¹⁴⁹ Daraweld® C's enhanced adhesive properties stand in opposition to the concept of shelter coating which is meant to be composed of like material that is compatible with the adobe so that it will naturally adhere. A three and a half gallon of Daraweld® C costs approximately \$250.¹⁵⁰

- **Acrylic Emulsions: Rhoplex™ E-330**
- **Rhoplex™ E-330:** Rhoplex™ E-330 is an acrylic emulsion manufactured by Dow Chemical Company via their subsidiary Rohm and Haas as an acrylic polymer resin

¹⁴⁷ DARAWELD® C: Bonding Agent for Concrete Repair ASTM C1059 Type II. Product Data Sheets, GCP Applied Technologies. <https://gcpat.com/en/solutions/products/daraweld-c>.

¹⁴⁸ *Ibid.*

¹⁴⁹ Hamilton, "Adhesives and Consolidants," 14.

¹⁵⁰ "GCP Applied Technologies Daraweld C 3.5 Gal. Interior/Exterior Bonding Agent," White Cap, <https://www.whitecap.com/p/gcp-applied-technologies-daraweld-c-35-gal-interiorexterior-bonding-agent-187333/24078/457daraweldc>.

designed for modifying Portland cement compositions. Five gallons of Rhoplex™ E-330 cost around \$150, making it significantly less expensive than Daraweld® C.¹⁵¹

Rhoplex™ E-330 is a polyaddition resin dispersed in water and acts as a thermoplastic. “Cement mortars mixed with this product are hard, tough and durable.” Rhoplex™ E-330 is a mixture of 46-48% acrylic polymers, 0.05% residual monomers, 0.3% aqua ammonia, and 52-54% water. The technical data sheet notes performance advantages of the product including durability and abrasion resistance, adhesion to a variety of surfaces, and resistance to discoloration. The glass transition temperature is noted as thirteen degrees Celsius, meaning that at this temperature the polymer can transition from the brittle glass like state to the softer and more malleable rubber like state.¹⁵² Acrylic emulsions obtain their properties from the substrate. In the case of adobe, “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 an important factor in understanding the relationship among soil types, [the acrylic emulsion], and their performance.”¹⁵³

Recent research on mortar samples amended with four different concentrations of Rhoplex™ E-330 displayed increased shrinkage upon drying. Higher concentrations of Rhoplex™ displayed the greatest shrinkage compared to samples with lower concentrations of the solution.¹⁵⁴ The current soils being tested at Fort Union require

¹⁵¹ “RHOPLEX E-330 Acrylic Emulsion Polymer Cement Modifier Additive 5 Gal,” EBay, <https://www.ebay.com/itm/125205447011>.

Note: A price estimate was requested directly from Dow Chemical and a response was still pending at the time of publication.

¹⁵² Rhoplex™ E-330: Acrylic Polymer. Technical Data Sheet. The Dow Chemical Company (“Dow”). July 2010.

<https://studylib.net/doc/10423205/rhoplex™-e-330>.

¹⁵³ Hartzler, “A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites,” 155.

¹⁵⁴ Dickensheets and Matero, 10.

further testing and an understanding of the percentage of Rhoplex™ being used, before Rhoplex™ E-330 is renewed for use in another season in 2022.

Surface treatments as preventive conservation methods for adobe walls have a longstanding history at Fort Union National Monument (see Appendix C, a summary of the treatment history by phases). While the treatment information and analysis are specific to the adobe walls at Fort Union, the methodology and conclusions are applicable to other earthen sites across the Southwestern United States and beyond. With the correct formula and application technique, shelter coating can allow historic earthen sites to be protected in situ with minimal visual disruption and hopefully prolong their status with minimal loss of the remaining original fabric. The goal of this section was to evaluate and update the existing treatment history to include the period of 1996 to 2022. The treatment history laid out here reveals the evolution of surface preservation throughout the life of the site to date. Five phases emerge from the literature, encompassing different practices and use of manufactured products across five chemical classes: silicones, polyvinyl acetates, plastics, epoxies and acrylic emulsions. Prior to 1981, products were applied directly to exposed adobe. Intended to be long-term solutions, these coatings failed prematurely due to incompatibility with the adobe walls and ultimately caused more damage than protection from surface loss. In 1981 the practice of shelter coating began in the form of unamended shelter coats which were destroyed in as little as a day by normal weather events. This led to the advent of the current phase of practice which uses soil shelter coats with an amendment to provide greater resistance to water sensitivity and adhesion of the shelter coat to the adobe substrate.

Though numerous products have been used throughout the years, laboratory and site testing has not been conducted at Fort Union since the mid-1990s. Analysis from these tests at Fort Union advocated for continued and long-term testing of products. Tests carried out at Fort Selden, New Mexico around this time indicated that although Rhoplex™ E330 had been recommended in earlier tests, El Rey Superior 200, a commercial product that uses Rhoplex™ E-330, displayed the best overall performance for earthen shelter coats in terms of erosion resistance. The report notes that soil properties are particularly critical when using an acrylic emulsion such as Rhoplex™ or El Rey Superior given that the soil is what imparts properties to the acrylic. Given staffing and budgetary limitations, Rhoplex™ E-330 continues to be used as an amendment to shelter coats without adequate testing to justify its properties. Based on what is known to date about the properties of acrylic emulsions in soil, including the recent literature regarding the use of Rhoplex™ E-330 in earthen mortars at Wupatki,¹⁵⁵ it was evident that further testing was required at FOUN. Testing of the product with the soil being used at FOUN was critical to understand how soil performance changes as the percentage of Rhoplex™ increases or decreases. The next chapter details the results of the tests conducted as part of this research.

¹⁵⁵ Dickensheets and Matero, 13.

Section 6: Material Characterization

The following details the soil characterization and geotechnical tests conducted on shelter coat formulations developed in the Architectural Conservation Laboratory at the University of Pennsylvania. The complete matrix of tests conducted and proposed testing for future research is included in Appendix B.

Soil Characterization Tests

Understanding soil performance is critical in earthen heritage conservation as soil structure varies significantly from site to site and lack of knowledge about earthen architecture and the materials being used is the major reason for failure at many earthen sites.¹⁵⁶ In the 2021 shelter coating season, which runs from May through September each year, FOUN began using a red soil from Tecolote, New Mexico which is approximately forty miles south of the site. In the 2020 season FOUN staff were using a brown soil from the Watrous area where FOUN is located. Choice of soils used in earthen construction and conservation is typically determined based on proximity to the site; soils closer to the site are often similar and therefore more compatible given similar grain size distribution, clay mineralogy, and comparability to the substrate. Both soils were classified by color using the Munsell system for soils.¹⁵⁷ Munsell color matching in the laboratory classified the 2021 “red” soil as a Dark Reddish Brown with 2.5YR and 3 value/4 chroma. The 2020 “brown” soil is classified as a Reddish Brown with 2.5YR and 4 value/3 chroma.

¹⁵⁶ Correia and Rosado, 85.

¹⁵⁷ “D1535-97, Standard Test for Specifying Color by the Munsell System,” (West Conshohocken, PA: ASTM, 1997).

In the process of mixing shelter coats on site, sand is added to both soils in the ratio of three soil to one sand by volume. This is based on in situ trial and error in terms of the feel of the soil, to improve grain size distribution and enhance performance including minimizing shrinkage of the shelter coats.

Preliminary Soil Characterization Tests on Red and Brown Soils

1. Particle size analysis (dry and wet sieve):

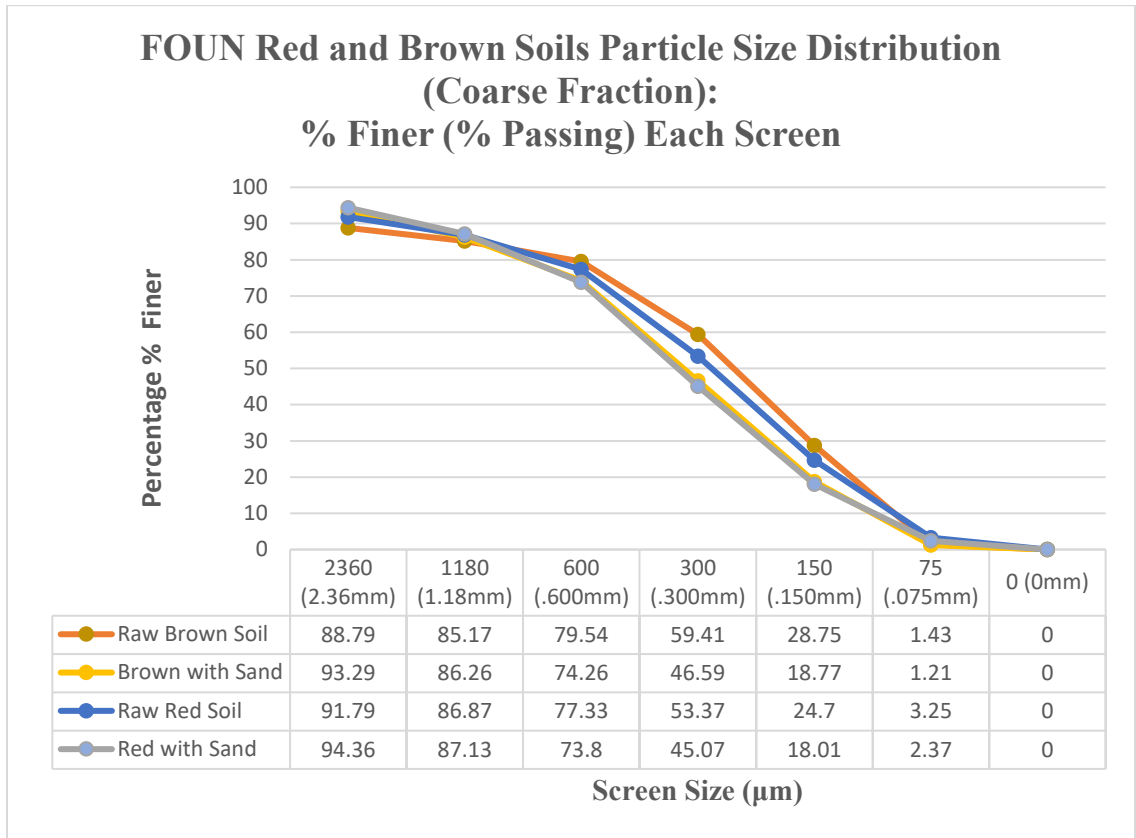
The combined dry and wet sieve test is conducted for soils with a high clay content. This was determined when the dry sieve test was conducted initially and could not be completed given the significant amount of fine clay that remained in each sieve. This test was conducted using the ASTM standard for particle-size distribution of fine-grained soils.¹⁵⁸

Initially, both soils were dry sieved, yet the significant presence of fine particles remaining on each sieve size indicated a highly clayey soil that required the sedimentation process to complete the test. The sedimentation test method uses a hydrometer to determine the percentage of particles smaller than the 75-micron (μm) sieve (silt and clay). The combined dry and wet sieve test determined the percentage of sand, silts and clays in the soil, which ultimately contribute to soil performance.

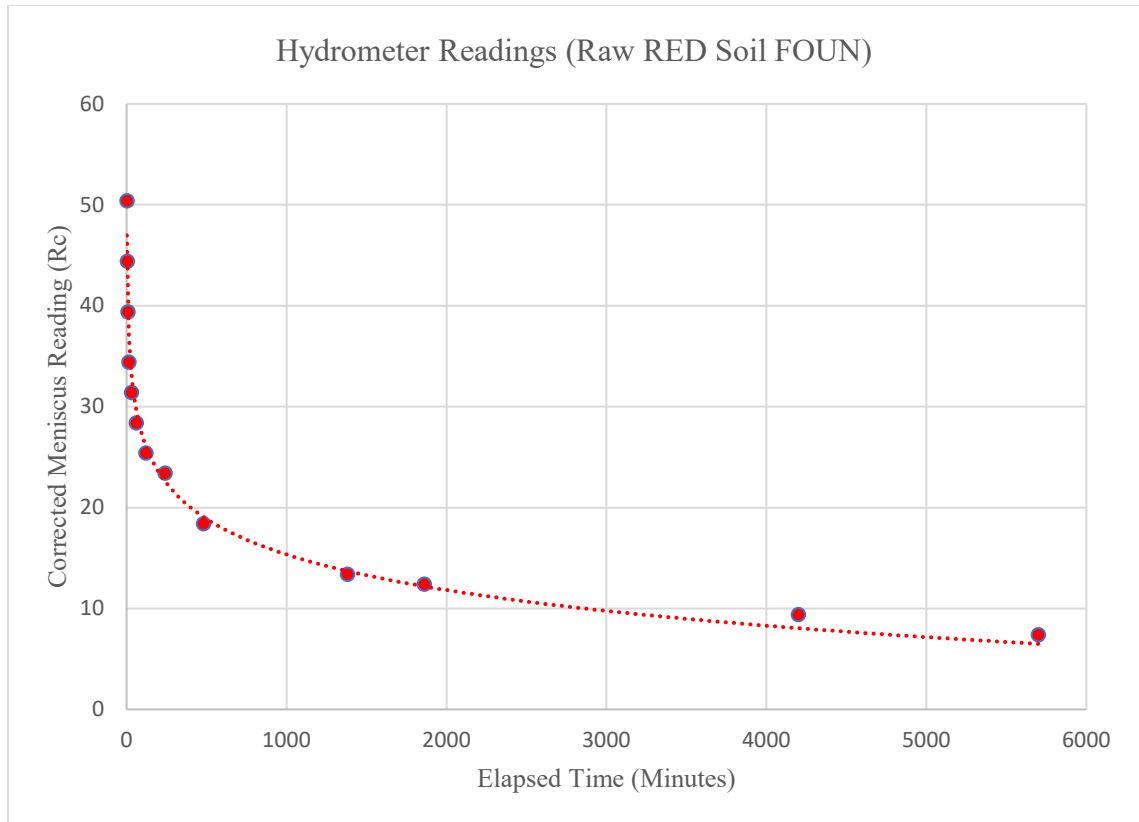
The particle size analysis of the coarse fraction of the raw brown and red soils was determined first, followed by analysis of the coarse fraction with the addition of sand. As FOUN adds sand to the shelter coat mixes, the addition of sand was important to understand how the sand affects particle size distribution. The sand was found to unify

¹⁵⁸ “D7928-21e1 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis,” (West Conshohocken, PA: ASTM, 2021).

the grain size distribution of both soils, as is indicated by the grain distribution curves (Graph 1).

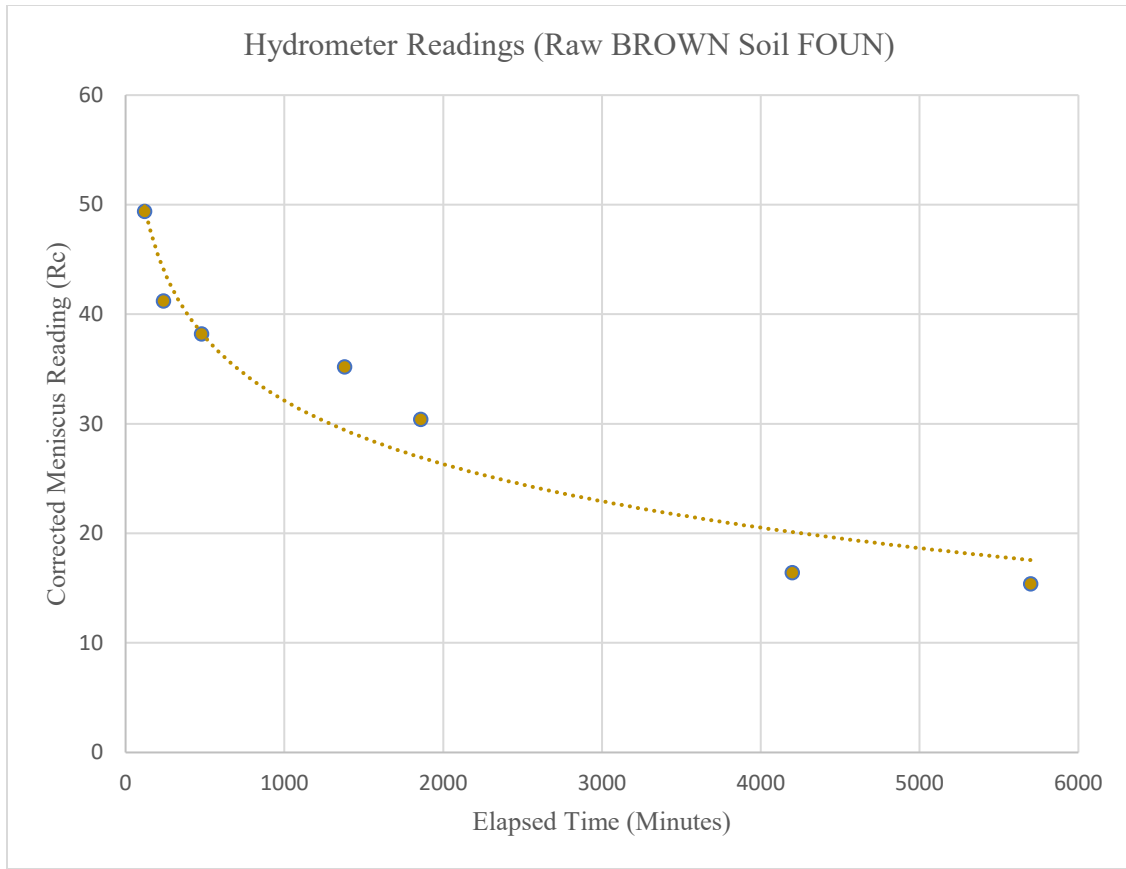


Graph 1: Raw Grain Size Curves (Coarse Fraction Only).



Graph 2: Hydrometer Readings Red Soil.

The hydrometer readings from the red soil indicate that the fine fraction contained approximately 36% silt, and 18% clay. The hydrometer reading remained above 60 for less than two minutes of testing, indicating a lower number of fines than the brown soil (Graph 2).

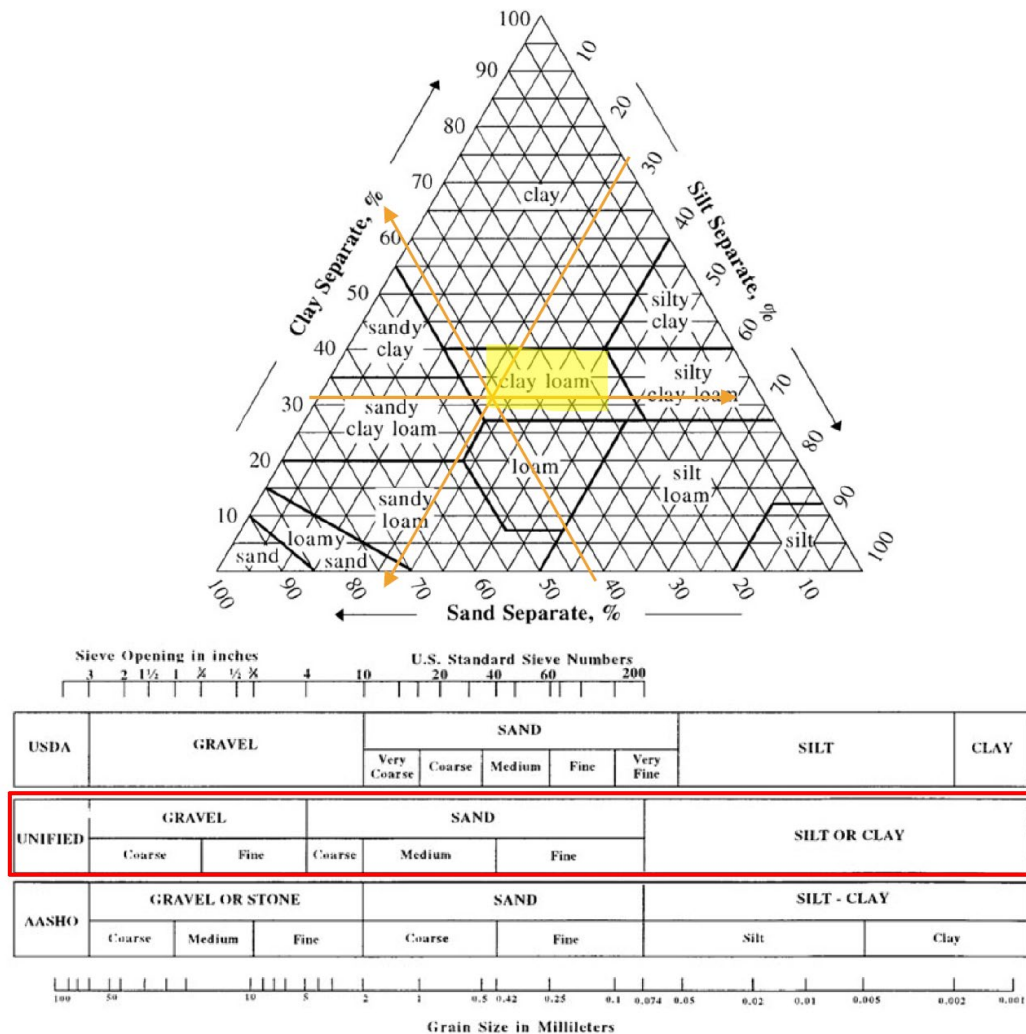


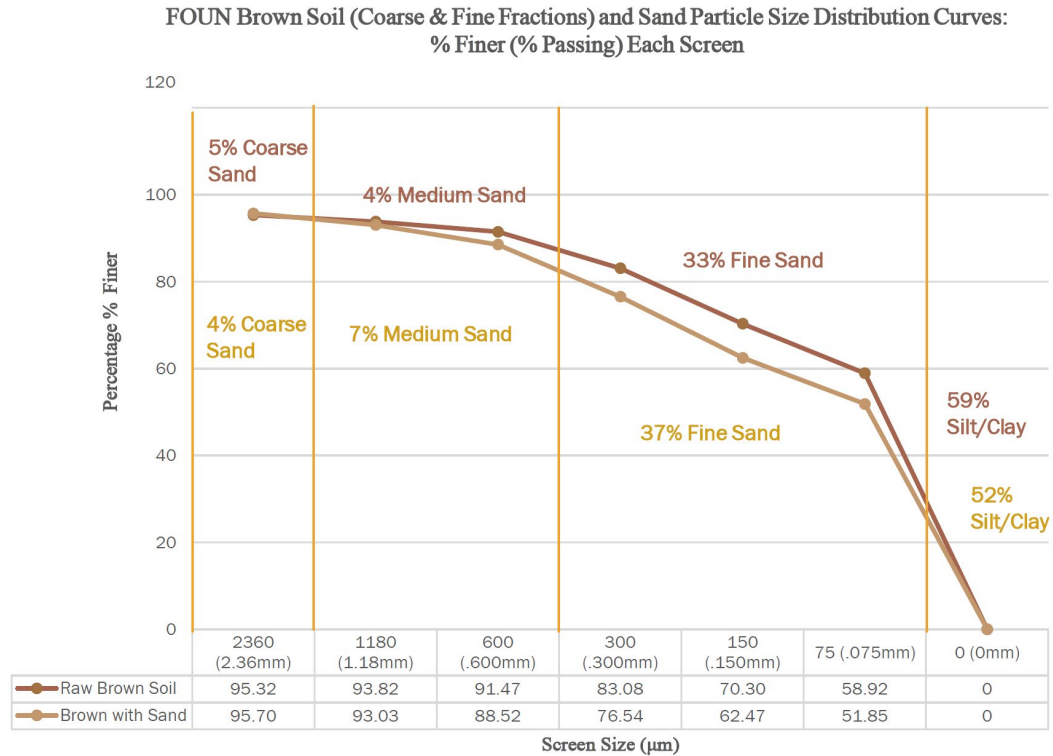
Graph 3: Hydrometer Readings Brown Soil.

The hydrometer readings for the brown soil indicated a highly clayey soil, with no measurable amount of silt. The number of fines in the brown soil was so high that the hydrometer reading remained greater than 60 for at least the first hour of testing. It was only possible to take the first hydrometer reading after two hours (120 minutes) of testing (Graph 3). The hydrometer readings indicated that the fine fraction of the brown soil contained over 27% clay (see Appendix D for the full sedimentation analysis and calculations).

Following the results of the liquid and plastic limits tests which indicated that the brown soil had the more optimal properties (detailed below), the brown soil was further classified using the soil texture triangle and a complete grain size distribution curve

including coarse and fine fractions from sedimentation. Analysis using the soil texture triangle and the unified system for soil analysis indicated that the brown soil is classified as a clay loam (Figure 18).¹⁵⁹





Graph 4: Brown soil coarse and fine fractions particle size distribution curve.

The addition of sand to the brown soil resulted in a more even distribution of particles to provide optimal consistency and to help with shrinkage upon drying (Graph 4). The addition of sand to the brown soil lowered the percentage of course sand increased the percentage of medium sand, while the percentage of fine sand increased, and the percentage of silt/clay decreased. Given that the hydrometer analysis revealed a significant amount of clay in the brown soil, the addition of sand will also increase the strength of the brown soil and decrease its propensity to shrinkage.

2. Liquid and Plastic Limits (Atterburg Limits): ASTM D4318-17e1

The Atterburg Limits tests are an important indication of soil performance and consistency. These tests were conducted using the ASTM standard test for liquid and

plastic limits, and the plasticity index of soils.¹⁶¹ The liquid limit test is a measure of the water content at which a soil begins to behave as a liquid. Liquid limit testing is conducted by smoothing the soil into a Casagrande device which is turned to measure the number of drops it takes for the groove in the soil to close (Figures 19-20). The test begins with the soil in a drier state, a higher number of drops required, to a wetter state, requiring a lower number of drops.



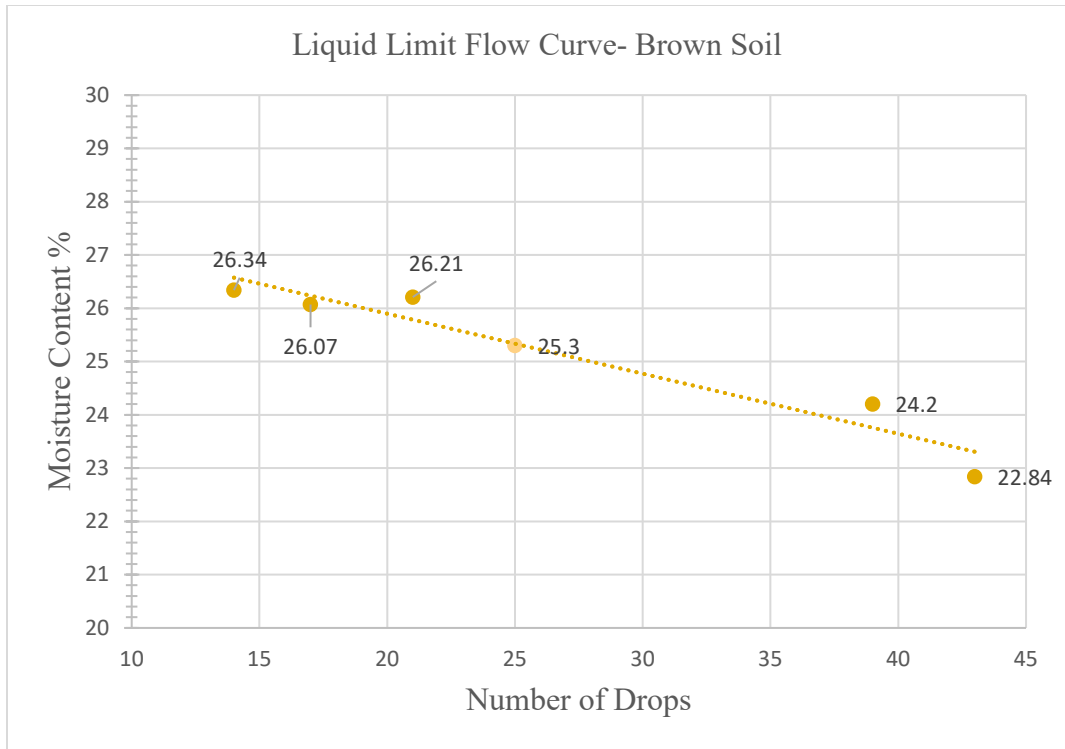
Figure 19: Casagrande device, used to measure liquid limit, with the center groove.

¹⁶¹ “D4318-17, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils” (West Conshohocken, PA: ASTM: 2017).

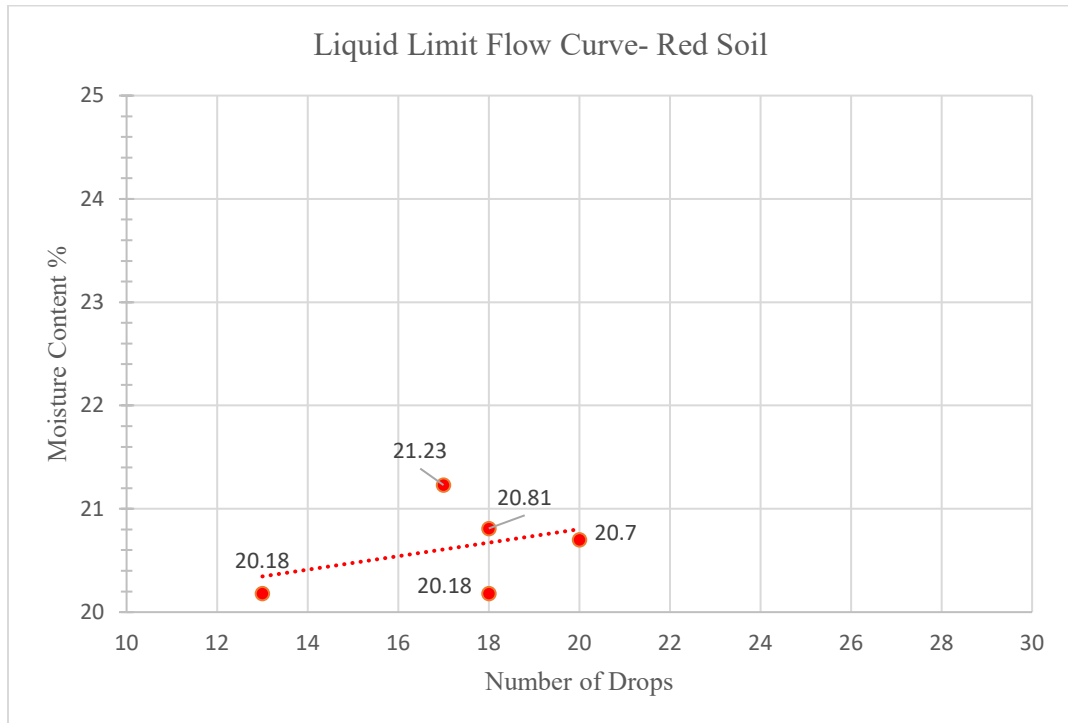


Figure 20: Casagrande device, used to measure liquid limit, without the center groove.

The raw brown soil had a high liquid limit of 25 (Graph 5) indicating that it was able to absorb a high amount of water before turning to its liquid state. The raw red soil was non plastic (Graph 6) – even at its driest state the soil performed poorly, meaning the liquid limit could not be determined.

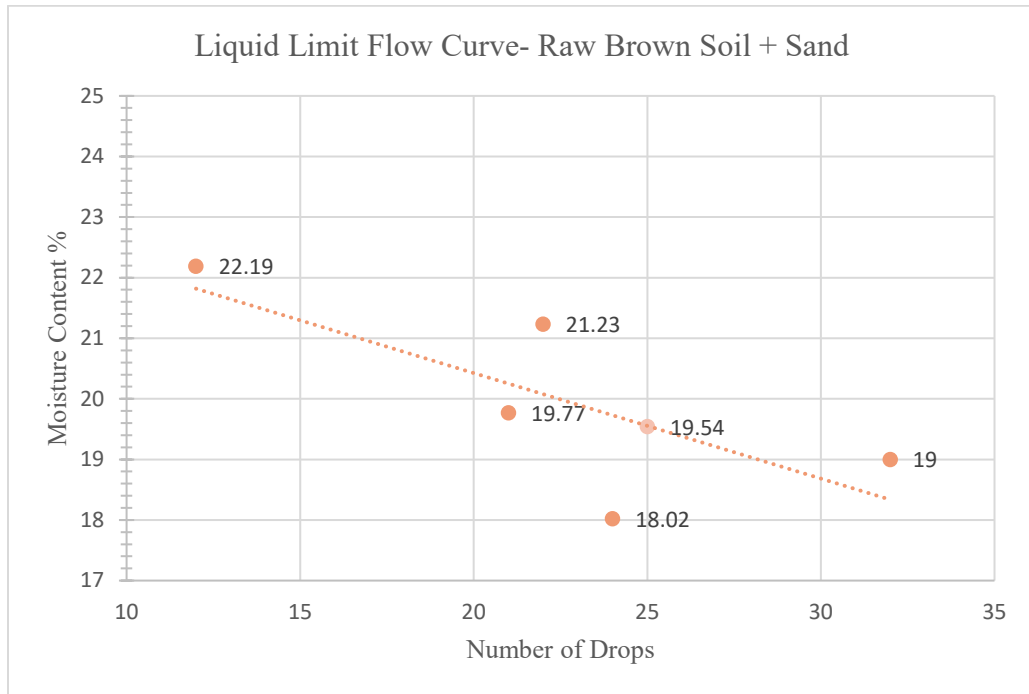


Graph 5: Brown Soil Flow Curve with a Liquid Limit of 25.

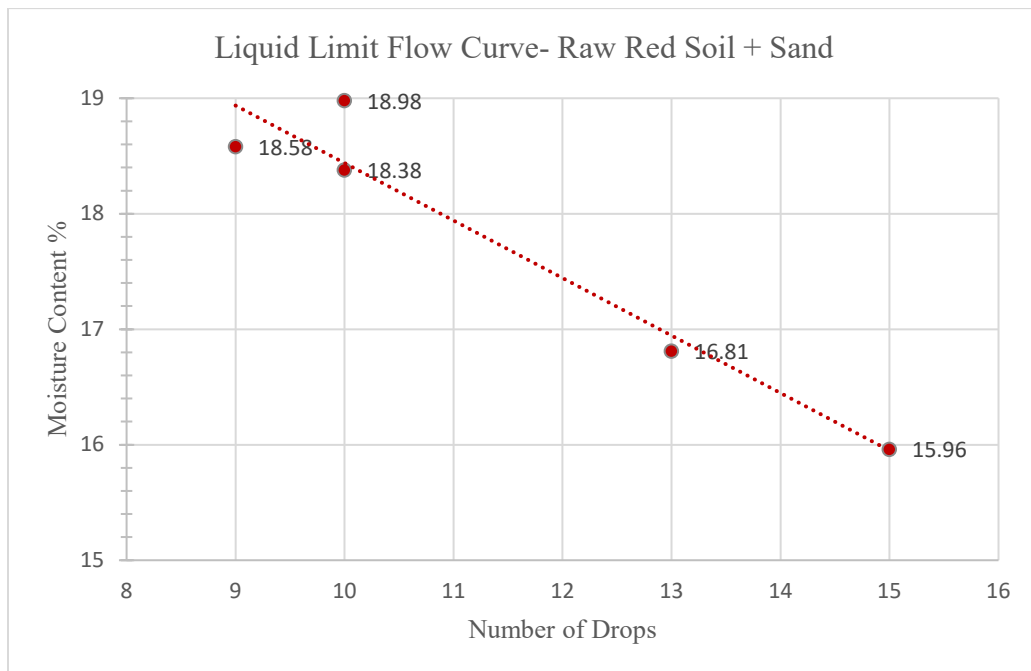


Graph 6: Red Soil Flow Curve, Liquid Limit could not be determined.

With the addition of sand, the brown soil had a slightly lower liquid limit of 20 (Graph 7), while the red soil's liquid limit could not be determined meaning that the soil is non-plastic (Graph 8).



Graph 7: Brown Soil and Sand Flow Curve with a Liquid Limit of 20.



Graph 8: Red Soil and Sand Flow Curve, Liquid Limit could not be determined.

The plastic limit of soil is the water content at which there is a change from a plastic to a semi solid state, at which the soil no longer behaves as a plastic or as a workable thread. The test involves rolling out the fine portion of the soil until it breaks – if the soil is at moisture content where it behaves as plastic, the thread will retain its shape as it is rolled out to a narrow diameter (Figures 21-22). The plasticity index is the range at which a soil's water content allows it to behave plastically and is determined by the calculated difference between the liquid and plastic limits.

The raw red soil ultimately proved to have limited plasticity and poor workability. Despite having a very high plastic limit at 107, the inability to determine the liquid limit meant that the soil was non-plastic or not cohesive. The red soil and sand had a lower plastic limit of 19, yet was also non-plastic given the inability to determine its liquid limit.

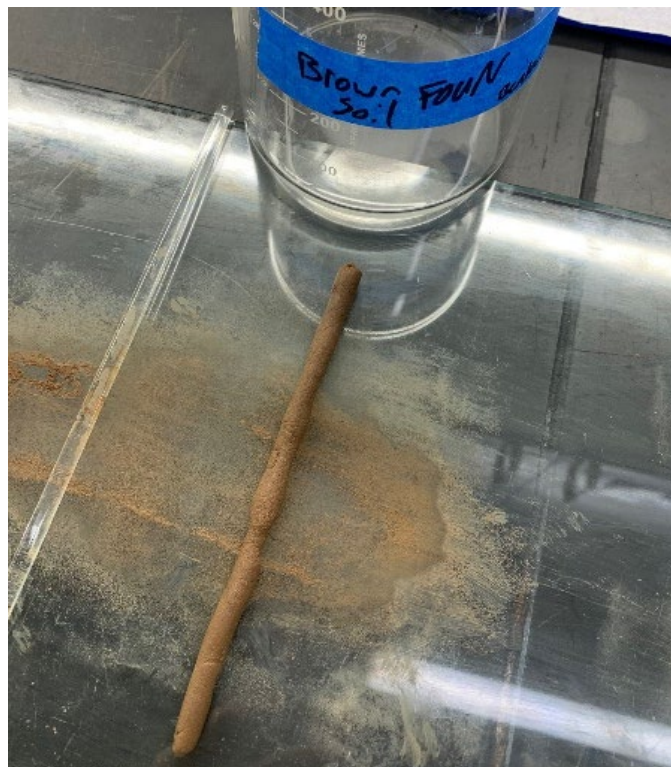
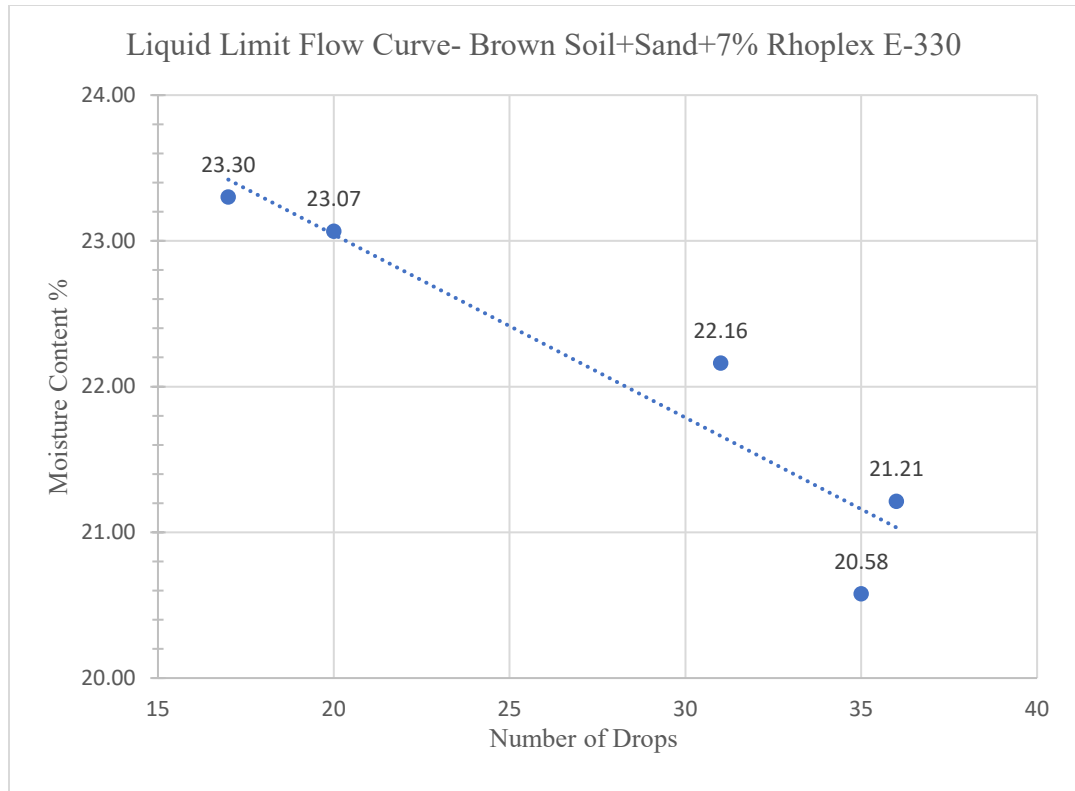


Figure 21: Plastic limit of raw brown soil.

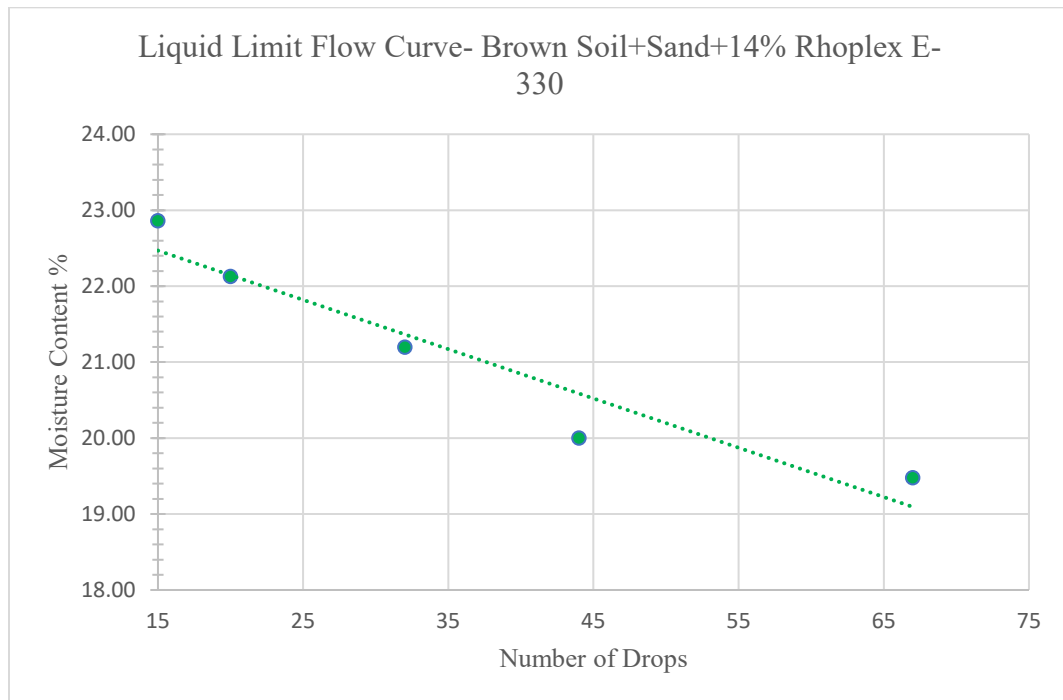


Figure 22: Plastic limit of raw red soil.

The raw brown soil had a workable consistency with a plastic limit of 15 and a plasticity index of 10. The addition of sand increased the brown soil's plastic limit to 18 and lowered the plasticity index to 2. Yet, the soil was still able to perform plastically, and the addition of the sand assists with overall shrinkage upon drying. The addition of concentrations of Rhoplex™ E-330 was also tested on the brown soil given its later selection for the performance tests. The differences between the plastic limits of the 7% and 14% Rhoplex™ were negligible; 18 and 17, respectively. The liquid limits for the 7% and 14% Rhoplex™ E-330 formulations were equal, both at approximately 22 (Graphs 9 and 10). This resulted in the 7% formulation having a plasticity index of 4, and the 14% formulation with a plasticity index of 5.



Graph 9: Liquid limit of soil with a 7% Rhoplex™ amendment.



Graph 10: Liquid limit of soil with a 14% Rhoplex™ amendment.

3. Soluble Salt Analysis

Salt concentration was determined using Merck indicator MQuant tabs to detect the presence of soluble salts, including chlorides (Cl⁻), nitrates (NO₃⁻) and sulfates (SO₄²⁻).¹⁶² ¹⁶³ The soils were soaked for one hour after which the MQuant test strips were submerged in the solution. Color changes were observed and matched with the color indicators on the MQuant strips labels. The color changes indicate the range of ions present, yet they do not provide a quantitative analysis.¹⁶⁴ Both soils contained low to moderate levels of each salt measured by individual MQuant tabs for sulfates, nitrates, and chlorides (Table 2).

Soluble Salt Analysis						
	Sulfates	Nitrates	Chlorides	Weight of sample	Amount of water	Temperature of solution
Red Soil	<200	top: white, Bottom: light purple 25/5.6	2.8 quant tab units: 0.013% NaCl	10.48g	10- 15ml	Room Temperature
Brown Soil	<200	top: white, Bottom: light/dark purple 50/11	3.2 quant tab units: 0.017%NaCl	10.5g	10- 15ml	Room Temperature

Table 2: Salt analysis per soil.

¹⁶² MQuant tabs were used to obtain measurements.

¹⁶³ Dickensheets, 47.

Iyer, "Performance Evaluation of Clay Grout Formulations for Structural Cracking in Historic Earthen (Mud Brick) Buildings," 47.

¹⁶⁴ Dickensheets, 47.

4. pH Test: ASTM D4972-19

The pH tests were conducted by submerging the soils in distilled water at room temperature for one hour, after which the pH strip was inserted in the solution.¹⁶⁵ The red soil was slightly acidic, while the brown soil had a relatively neutral pH.

pH Test Results				
	pH reading	Weight of sample	Water (ml)	Temperature of Solution
Red Soil	6	10g	About 25ml	Room Temperature
Brown Soil	6.5-7	10.45g	About 25ml	Room Temperature
Distilled Water	6.5	-	About 25ml	Room Temperature

Table 3: pH test per soil.

5. Carbonate Content

The carbonate content test is an adaptation of the gravimetric mortar analysis lab test and follows the standard ASTM test method.¹⁶⁶ This adaptation was conducted using the acid digestion method utilizing 15% HCl.¹⁶⁷ The samples were dried to a constant mass, weighed and then submerged in the HCl solution, after which the solution was diluted with deionized water and agitated. Following complete acid digestion, the solution of fines was poured onto a piece of pre-weighed filter paper and left to drain. Once the fines were collected on the filter paper, they were dried in the oven for 24 hours and weighed to obtain the weight of the fines. The test measures the acid soluble content of a soil, which can inform soil stability and performance. Natural carbonates are common in

¹⁶⁵ “D4972-19 Standard Test Methods for pH of Soils,” (West Conshohocken, PA: ASTM, 2019).

¹⁶⁶ “D4373-21 Standard Test Method for Rapid Determination of Carbonate Content of Soils,” (West Conshohocken, PA: ASTM, 2021).

¹⁶⁷ Iyer, 40.

Southwestern soils (Table 4). The tests indicated the brown soil contained a higher carbonate content (1.8%) than the red soil (0.5%).

Carbonate (Acid-Soluble) Content				
Soil	Dry Sample Mass (g)	Mass after acid digestion (g)	Mass of Acid Soluble Fraction (g)	% Acid Soluble
Red	30.22g	30.07g	0.15g	0.5%
Brown	28.67g	28.15g	0.52g	1.8%

Table 4: Acid-soluble content per soil.

6. Methylene Blue Adsorption Test¹⁶⁸:

The methylene blue adsorption test is based on the French standard AFNOR NF P 94-068-1998 which proposed the use of the spot method (Figures 23-24). The test is a reliable way to determine the presence and properties of clay minerals in soils early during the first stages of testing.¹⁶⁹ Methylene blue is added to the solution and a drop is added to a piece of filter paper via pipette at one-minute intervals until a light blue halo is consistently observed for five minutes. If a high amount of methylene blue is adsorbed, as is indicated by the total mL of methylene blue solution or the number of spots it takes before the blue halo persists, this may indicate the presence of swelling clay minerals such as montmorillonite and smectite which can cause instability in soils.¹⁷⁰ Low values of adsorption indicate the presence of a low amount of swelling clay or a certain amount of non-swelling clay.¹⁷¹ The brown soil adsorbed approximately 65ml of methylene blue,

¹⁶⁸ Iyer, 65.

¹⁶⁹ Tamer Topal, 1996, "The Use of Methylene Blue Adsorption Test to Assess the Clay Content of the Cappadocian Tuff." *In Proceedings of the 8th International Congress on Deterioration and Conservation of Stone, Berlin, Germany, September 30-October 4, 1996*, 791-799. Berlin, Germany: Geological Engineering Department, Middle East Technical University. <https://iscs.icomos.org/pdf-files/Berlin1996/topal.pdf>.

¹⁷⁰ Iyer, 67.

¹⁷¹ Topal, "The Use of Methylene Blue Adsorption Test to Assess the Clay Content of the Cappadocian Tuff," 791-799.

while the red soil adsorbed 40ml, and the following calculations were used to determine the clay properties present.

The test allows the index of activity (V_b) of clay minerals to be calculated as follows:¹⁷²

$$V_b = V \times 0.01 \times 100 / W$$

V_b = the activity index of the material in g/100g,

V = volume of methylene blue solution used,

0.01 = the concentration of the methylene blue solution, and

W = the dry weight of the sample used

The index of activity can only be determined if the sedimentation or hydrometer analysis was conducted, as was the case with this research:

$$ACB = 100 V_b / CC$$

ACB = the index of activity (in g of methylene blue in 100g clay fraction),

V_b = the index or methylene blue value of the material (g/100g)

CC = the clay content (%) determined by hydrometer analysis

A low index of activity suggests a stable soil, while a high value indicates the presence of swelling clays. The brown soil's index of activity was 0.037 based on 27% clay content, and the red soil was calculated at 0.036 based on 18% clay content, indicating the presence of stable clays in both soils.

The following calculation is used to indicate the amount of methylene blue that was adsorbed and can be calculated without the sedimentation (hydrometer) analysis, allowing the analysis to inform early testing:

¹⁷² Iyer, 70.

$$SA = (VB/100) * (N/WMB) * (130*10^{-20})$$

SA = total active specific surface (m²/g),

VB = the active index of the material in g/100g,

N = Avogadro's number (6.02*10²³), and

WMB = molecular weight of methylene blue (320g)

If the surface area value (SA) is within the range of 20 m²/g to 800 m²/g it indicates clay minerals may be present, and if the value ranges between 1 m²/g to 4m²/g it suggests the presence of inert materials.¹⁷³ The brown soil's surface area value (SA) was 25.68 m²/g, while the red soil's SA value was 16.14 m²/g.

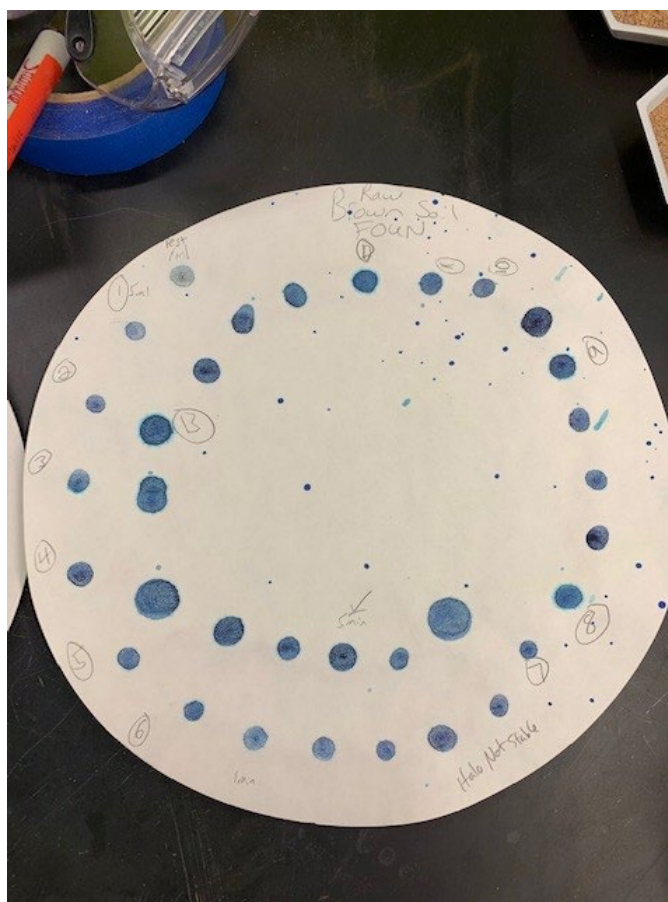


Figure 23: Methylene Blue Test Brown Soil.

¹⁷³ Iyer, 71.

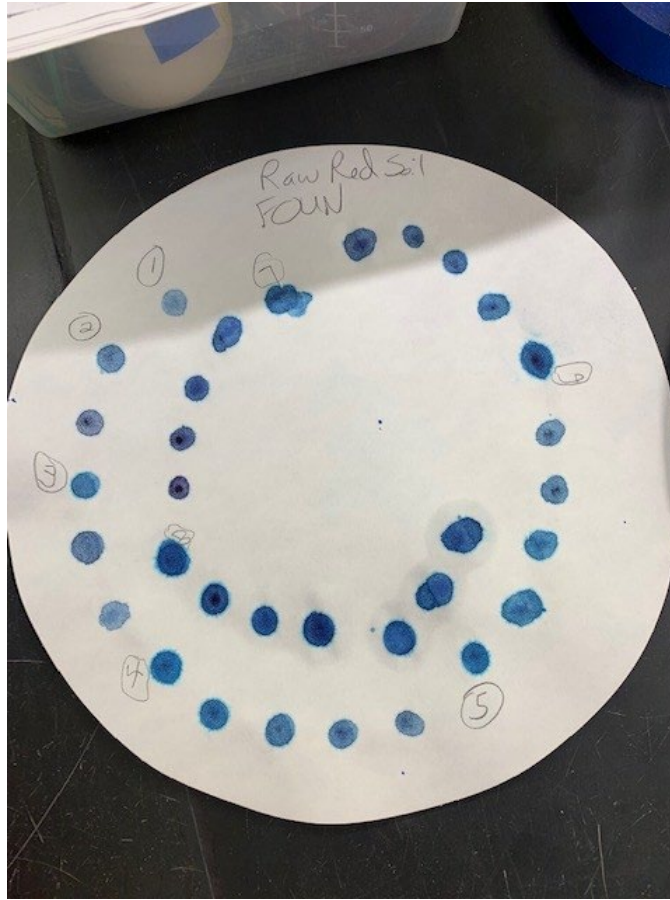


Figure 24: Methylene Blue Test Red Soil.

Preliminary and Confirmatory Performance Tests on Brown Soil

The results of soil characterization tests informed which soil moved forward into the preliminary and confirmatory performance test stages. Ultimately the brown soil was confirmed for further testing as it performed better and demonstrated more optimal characteristics for shelter coating in the soil characterization tests as denoted above. The results of the plastic and liquid limit tests were particularly important given the shelter coat's role as a sacrificial layer. The red soil, despite being the soil which FOUN is currently using as of the 2021 season, did not meet the standards for optimal criteria

based on the soil characterization tests, particularly the liquid and plastic limit testing which determined that the soil was non-plastic in its raw state and with sand added.

Regarding the preliminary and performance tests on the brown soil, Rhoplex™ E-330 at the current percentage used at FOUN (14%) was tested. Previous studies that tested Rhoplex™ E-330 suggested lower amounts of Rhoplex™ E-330 performed better and demonstrated greater plasticity, while higher amounts of Rhoplex™ were more brittle.¹⁷⁴

Adobe and Shelter Coat Mixing

Adequate mixing of soils is a critical component of testing to ensure that the samples prepared are fully representative of the material from which they are taken.¹⁷⁵ Full adobe bricks from FOUN were broken apart with a hammer and ground through a hand mill in the lab. The crushed adobe blocks were then mixed thoroughly in a Hobart C-100 mixer, water was added to create a thick paste, after which the paste was molded into adobe disks (Figures 25-27).

The adobe disks were left to dry on lab mats covered with paper towel, and they were covered with wet (wrung out) burlap for 24 hours and then left to dry.

¹⁷⁴ Hartzler, "A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites," 175.

¹⁷⁵ Jeanne Marie Teutonico, *A Laboratory Manual for Architectural Conservators* (Rome, Italy: ICCROM, 1988), 10.



Figure 25-26: (Upper) Author making adobe disks with molds, (Lower) Adobe disks drying in the lab



Figure 27: Hobart c-100 mixer used to mix adobe bricks, and shelter coat formulations.

Similarly, shelter coat formulations were mixed using the Hobart C-100 mixer. Prior to mixing, the raw brown soil was sieved through a $\frac{3}{4}$ " sieve to remove the largest particles as is the practice on site at FOUN. Sand was then added to the soil in a 1:3 ratio of sand to soil (by volume), also replicating the same process carried out on site (Table 1). Three shelter coat formulations were then mixed based on current site practices: 1) unamended soil, using only water to reach the desired consistency, 2) soil with a 14% Rhoplex™ E-330 solution, and 3) soil with a 7% Rhoplex™ E-330 solution. The desired consistency for shelter coats based on the ratios of materials provided by FOUN (Table 1) can be described as a mud that maintains its shape when dropped or thrown onto a wall yet is easily spreadable and more wet than the adobe paste. It can be easily smoothed

onto an adobe surface by hand without friction or resistance. During the mixing procedures, it was necessary to add a small amount of water to the soil alongside the Rhoplex™ E-330 to enhance the formulation's workability or consistency.

The decision to test a lower percentage of Rhoplex™ E-330 rather than another additive was based on previous testing of Rhoplex™ in mortars¹⁷⁶, and shelter coat tests, which are limited to the surface treatment tests conducted at Fort Selden, NM in the 1980s. The Fort Selden field tests tested Rhoplex™ E-330, among other products, in percentages ranging from 6%, to 12.5%, 25% and 33%; results from these tests noted that the soils became more brittle as the amount of Rhoplex™ E-330 increased. Ultimately the field tests report called for laboratory testing of the product in shelter coats, a recommendation that had not been followed through on until this research.¹⁷⁷ Based on this information the decision was made to half the amount of Rhoplex™ E-330 currently used on site, from a 14% solution to a 7% solution diluted with water.

Ratios According to the FOUN Masonry Mix Guidelines
1 Sand : 3 Soil
1 Rhoplex E-330 : 7 Water (creates a 14% solution)
1 Rhoplex solution : 9 Soil/Sand Mix

Table 1: Ratios by volume for shelter coat formulations according to FOUN Masonry mix guidelines as provided by FOUN.

Each shelter coat formulation was then applied by hand using rubber gloves to adobe disks at ¼" thick (Figure 28), based on practices observed on site at FOUN in October 2021. The samples were left to dry on lab mats covered with paper towels, and

¹⁷⁶ Dickensheets, 155.

¹⁷⁷ Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 20.

they were covered with wet (wrung out) burlap for 24 hours and then left to dry for 3-5 days before being used for testing.



Figure 28: Adobe disks shelter coated with formulations at ¼" thick.

1. Shrinkage

The shrinkage test method for soils is a qualitative test created by the Architectural Conservation Lab at the University of Pennsylvania.¹⁷⁸ Shelter coat formulations were mixed to the desired consistency and were then troweled in terracotta saucers. The formulations, based on formulation from FOUN (Table 1), were too thick to be poured into the saucers as has been done in previous research dedicated to grout and mortar testing.¹⁷⁹ The terracotta saucers were soaked in water for at least twenty-four hours prior to conducting the test to ensure that the saucer would not absorb the water and

¹⁷⁸ Qualitative Shrinkage Test using terracotta saucers, by the University of Pennsylvania's Architectural Conservation Laboratory.

¹⁷⁹ Dickensheets, 147; Iyer, 75.

prematurely dry the soil and cause excessive shrinkage. Upon drying, the measure of shrinkage away from the inner edge of the saucer was measured with a digital caliper and compared. Low shrinkage is one of the optimal properties required for earthen shelter coats to minimize water infiltration from cacking and separation from the adobe substrate; prior to the addition of any amendments the raw soil should display low shrinkage on its own. Previous research on soil mortar formulations found that shrinkage increased with addition of higher concentrations of Rhoplex™ E-330.¹⁸⁰

Two formulations were initially tested in the qualitative shrinkage test, including 1) raw brown soil, and 2) raw brown soil and sand. Lab conditions during testing were recorded as 21° C, and 33% relative humidity (RH). The brown soil plus sand visually displayed less shrinkage around the perimeter of the disc than the raw soil, confirming the assumption that the addition of sand improved the soil's resistance to shrinkage (Figures 29 and 30). This was also the final determination to move forward with the brown soil plus sand for the remainder of the performance tests conducted.

¹⁸⁰ Dickensheets and Matero, 7.



Figure 29: Raw brown soil displayed greater shrinkage in the saucers.



Figure 30: Brown soil plus sand displayed less shrinkage in the saucers.

2. Consistency or Slump Test:

The slump test is a quantitative measure of a soil's consistency.¹⁸¹ The test was conducted using a Humboldt flow table and the H-3622M metric flow mold with the dimensions 70mm/100mm diameter by 50mm high.¹⁸² Each formulation was tested, including unamended, 7% and 14% Rhoplex™ E-330.

The mold was placed at the center of the flow table before filling it with the shelter coat formulation. The formulation was placed in the mold one layer at a time, tamping each layer 20 times to ensure that the mold was uniformly filled. Once the mold was filled the shelter coat was troweled to a plane surface, flush with the top of the mold, and allowed to sit for one minute (Figure 31). After lifting the mold away from the shelter coat, the flow table was dropped 25 times in approximately fifteen seconds. The diameter of the mortar was then measured four times across the lines etched in the flow tabletop (Figure 32). Shelter coats must be wet enough to be plastic and have a workable consistency. Yet, if the formulations are too wet they may shrink excessively, while too dry they will not adhere to the substrate. The slump test or consistency test provides a quantitative measurement of this.

¹⁸¹ "C 230/C230M-21: Standard Specification for Flow Table for Use in Tests of Hydraulic Cement," (West Conshohocken, PA: ASTM, 2021);

"C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar," (West Conshohocken, PA: ASTM, 2020).

¹⁸² "Flow Molds," Humboldt Mfg. Co., updated 2022, <https://www.humboldtmfg.com/flow-mold.html>.



Figure 31: Formulation in mold on flow table.



Figure 32: 14% formulation with the mold removed.

The consistency (flow) is “the resulting increase in average base diameter of the mortar mass, expressed as a percentage of the original base diameter.”¹⁸³ Original base diameter of the flow was 100mm. The flow is calculated by dividing “A” by the original inside base diameter in millimeters and multiplying by 100. “A” is the average of the four readings in millimeters, minus the original inside the base diameter in millimeters.

The unamended formulation had the highest percentage of flow at 29%. The higher percentage of 14% Rhoplex™ E-330 resulted in a lower flow, at 24% (Table 5). The results indicated that Rhoplex™ E-330 reduced the flow consistency or workability of shelter coat formulations. This was evident in the mixing procedures, during which it was necessary to add a small amount of water to the soil along with the Rhoplex™.

Flow Table Readings and Calculations			
Readings (mm)	Unamended	7% Rhoplex	14% Rhoplex
1	128.15	126.91	123.93
2	128.26	126.26	124.55
3	130.07	127.01	124.1
4	129.05	128.68	123.88
Average in mm	128.88	127.21	124.11
Original Diameter (mm)	100	100	100
A (average minus original diameter)	28.8	27.21	24.11
Flow %	29%	27%	24%

Table 5: Flow table readings and calculations.

¹⁸³ “C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar,” (West Conshohocken, PA: ASTM, 2020).

3. Water Drop, Depth of Erosion:

The water drop erosion test is not a published standard, it was developed by CRAterre to determine the mechanical action of falling water on earthen surfaces. Previous laboratory theses describe the procedure in detail.¹⁸⁴ The test measures the depth of erosion on a sample when exposed to the direct impact of falling water. Each shelter coated adobe sample, including unamended, 7% and 14% Rhoplex™ E-330, was dried in the oven for twenty-four hours prior to testing. Each sample was then fitted with a circular PVC mold to protect the shelter coat from being dislodged during the test (Figure 33). Burets were filled with deionized water and were set to disburse one drop of water every second for one hour, falling from a height of approximately 2.6 meters (Figures 34-35).



Figure 33: Unamended shelter coat after only one minute of testing, fitted with a circular mold.

¹⁸⁴ Zinn, 60-62.



Figure 34: Water drop erosion burettes set up.

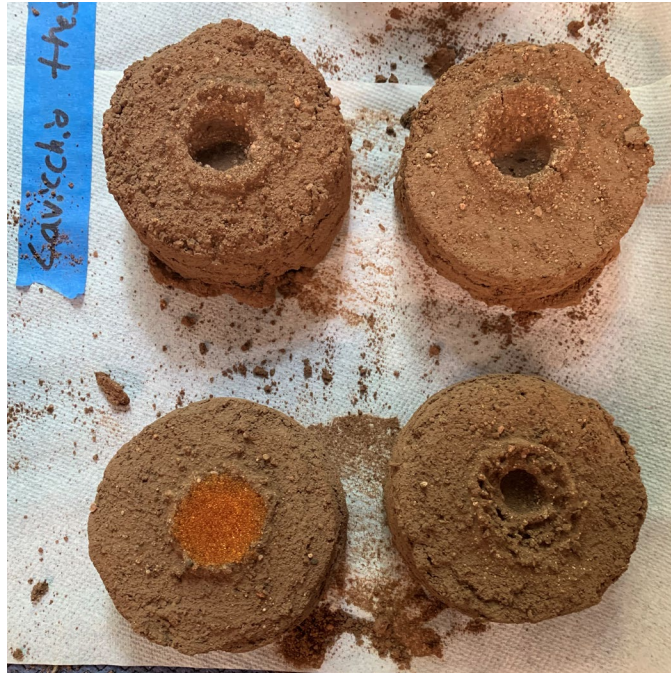


Figure 35: Water drop erosion full set up.

Following the test, samples were left to dry in the plastic containers given that they were too fragile to move. After the samples were thoroughly air dried, they were treated in the oven for twenty-four hours. To measure the precise depth of erosion, an approach was adopted using glass microbeads. The hole formed by the falling water was

filled with glass microbeads flush to the surface (Figure 39), overturned into a pre-weighed weighing boat, after which the weight of the beads in grams and the volume of the beads in cubic centimeters was determined. The greater the weight or volume of the beads, signified a higher depth of erosion.

The unamended samples were thoroughly eroded through to the adobe disk, while the 7% amended samples performed slightly better in terms of erosion resistance. The 14% amended samples saw almost no erosion; the imperceptible holes in these samples were not measurable (Figure 36-38). The average depth of erosion on the unamended samples was 3.5 cubic cm (standard deviation: 0.69 cubic cm), and 2.6 cubic cm (standard deviation: 0.49 cubic cm) on the 7% amended samples (Tables 6-7) suggesting a reduction in erosion of nearly 26%. The depth of erosion in cubic centimeters for the unamended and 7% samples was compared through an f-test and a t-test (Table 6-7). The f-value of 0.58 and t-value of 0.04 indicate that there were no significant outliers and the difference in variances between the samples is not statistically significant.



Figures 36-37: Water drop erosion results on 1) unamended soils (upper), 2) 7% shelter coats (lower).



Figure 38: Water drop erosion results on 14% shelter coats.



Figure 39: Glass microbeads filling the hole on an eroded unamended shelter coat.

Sample	Depth of erosion (volume in cubic cm)	Rate	Temperature and humidity during experiment
A. Unamended	3.1	One drop per second for one hour (3600 drops)	17.6° C, 24-25% humidity, final sample at 19° C, 33%RH
B. Unamended	2.8		
C. Unamended	3.6		
D. Unamended	4.4		
Average	3.5		
Standard Deviation	0.69		
F Test	0.58		
T Test	0.04		

Table 6: Depth of erosion of unamended samples.

Sample	Depth of erosion (volume in cubic cm)	Rate	Temperature and humidity during experiment
A. 7%	3.1	One drop per second for one hour (3600 drops)	17.6°C, 24-25% humidity, final sample at 19°C, 33%RH
B. 7%	2.9		
C. 7%	2.4		
D. 7%	2		
Average	2.6		
Standard Deviation	0.49		
F Test	0.58		
T Test	0.04		

Table 7: Depth of erosion of 7% Rhoplex™ E-330 samples.

4. Water Drop, Absorption

The final performance test conducted on the shelter coats was the water drop absorption test, known as the microdrop test.¹⁸⁵ The test presents a method to measure the change in properties of treated and untreated masonry surfaces.¹⁸⁶ The measurement of the absorption rate of one drop of water, and the subsequent desorption rate of the drop, is a test of water repellency of the surfaces. The test was developed by UNESCO, Rilem and is detailed in the Laboratory Manual for Architectural Conservators.¹⁸⁷

Samples were dried in an oven at 60°C for twenty-four hours and cooled to room temperature before testing. Ensuring the samples are fully cooled is critical as warmer samples may result in faster absorption and desorption rates. A 1ml pipette was used to drip a single drop of distilled water onto the sample at approximately 1cm from the surface (Figure 40). At the same time, a single drop was added to a glass surface to serve as a reference (Table 8).

¹⁸⁵ UNESCO, Rilem, "Water drop absorption," In *International Symposium on Deterioration and protection of stone monuments: experimental methods*. Paris, France, Volume V, Test II. 8b: (1978); Teutonico's *A Laboratory Manual for Architectural Conservators*, 42-45.

¹⁸⁶ Teutonico, *A Laboratory Manual for Architectural Conservators*, 40.

¹⁸⁷ UNESCO, Rilem, "Water drop absorption," 42-45.



Figure 40: 1ml pipette used to drop one droplet of water onto the shelter coat.

As soon as the drop of water reached the surface of the sample, a stopwatch timed the absorption rate. Once the drop was fully absorbed, timing began to measure the rate of desorption (Tables 8-9).

Glass as Reference Surface	Evaporation time on glass surface (te)	Temperature and humidity during experiment
Drop start: 4:20pm	5100 seconds	21.2°C, 31% humidity
Drop Evaporation: 5:45pm		

Table 8: Glass reference surface rate of evaporation.

Sample	Absorption time into treated surface (tx)	Absorption time into untreated surface (tn)	Evaporation or desorption time on the sample surface (Te)	Temperature and humidity during experiment
A. Unamended	-	0 seconds (immediate)	590 seconds	21.2°C, 29-31% humidity
B. 7% Rhoplex	17 seconds	-	896 seconds	
C. 14% Rhoplex	290 seconds	-	1241 seconds	

Table 9: Average rates of absorption and desorption based on three rounds (Appendix E) with the unamended sample as the reference surface.

The absorption (WA) of treated and untreated surfaces is calculated as a percentage. Two calculations, using the glass reference surface first, and then using the unamended sample as the reference, were compared. If Tx is less than 0.05, the following formula is used:

$$WA = [1 - (tx - tn)/tx] \times 100$$

$$WA = \text{absorption \%}$$

Tx = absorption time into a treated or weathered surface

Tn = absorption time into the reference untreated surface

If Tx is greater than 0.05, the evaporation time (Te) must be taken into consideration. The evaporation time (Te) was considered using the following formula:

$$WA = [1 - (tx - tn)/(te - tn) \times (te/tx)] \times 100$$

$$WA = \text{absorption \%}$$

Tx = absorption time into a treated or weathered surface

Tn = absorption time into the reference untreated surface

Te = evaporation time

Ultimately the second formula considering evaporation time of the samples was adopted given that the evaporation times were greater than 0.05. For comparison both the unamended sample's evaporation time (T_e) and the evaporation time (T_e) from the glass reference surface were calculated (Table 10).

Sample	Unamended Sample as T_e Reference	Glass Surface as T_e reference
A. Unamended	100% WA, 0% WR	100% WA, 0% WR
B. 7% Rhoplex	3% WA, 97% WR	10% WA, 90% WR
C. 14% Rhoplex	1% WA, 99% WR	1% WA, 99% WR

Table 10: Water Absorption (WA) and Water Repellency (WR) rates compared using the unamended sample vs. glass surface as references.

Unamended sample as reference for T_e :

- Water absorption rate of the unamended sample in both cases was 100% given that the drop was immediately absorbed.
- The 7% Rhoplex™ E-330 shelter coat had a 3% water absorption rate..
- Water absorption of the 14% Rhoplex™ sample was 1%.

Water repellency (WR) is calculated as:

$$WR (\%) = 100 - WA$$

- Unamended shelter coats had a water repellency of 0%.
- The 7% Rhoplex™ E-330 shelter coat had a 97% water repellency rate.
- The 14% Rhoplex™ sample had a rate of 99% water repellency.

Glass surface as a reference for Te:

- Water absorption rate of the unamended sample was 100%.
- The 7% Rhoplex™ E-330 shelter coat had a 10% water absorption rate, a higher rate of absorption compared to using Te from the unamended sample as reference.
- The water absorption rate of the 14% Rhoplex™ sample was constant at 1%.

Water repellency (WR) is calculated as:

$$WR (\%) = 100 - WA$$

- Unamended shelter coats had a water repellency of 0%.
- The 7% Rhoplex™ E-330 shelter coat had a 90% water repellency rate.
- The 14% Rhoplex™ E-330 sample remained constant at a rate of 99% water repellency.

The 7% and 14% Rhoplex™ E-330 shelter coats both displayed high water repellency rates. The slow desorption rates for the unamended and Rhoplex™ amended samples (Table 9) is another important factor that requires further study in the field and lab given that shelter coats perform best if their water absorption rates are low. If absorption rates are high, then desorption rates need to be high as well meaning they should dry quickly. Reducing water into the shelter coat and adobe below as well as removing any absorbed water quickly is critical to wall preservation.

Section 7: Discussion and Conclusions

Shelter coat performance should satisfy critical optimal properties as identified through the laboratory testing conducted throughout this research. These properties include good consistency (plasticity) and adhesion during application, low shrinkage, and good resistance to weathering including good cohesive strength and weatherability (durability). Low liquid-water absorption and high desorption, and moderate water-vapor permeability are also critical.¹⁸⁸ A cohesive shelter coat is critical at earthen sites that employ this practice as a method of preventive conservation, otherwise the adobe will severely deteriorate as it is unprotected and exposed to the elements over time. Limited research on shelter coating exists to date and has long been in demand. As weather events at Fort Union National Monument (FOUN) increase in frequency and severity the need for continued research and testing (both in the laboratory and field) of these protective sacrificial layers is critical.

Rhoplex™ E-330, an acrylic polymer emulsion, has been used as a soil amendment in the southwestern United States since the 1970s, though its compatibility for use in shelter coats has not been thoroughly tested. Studies of Rhoplex™ E-330 in earthen mortars suggest that its performance depends on the emulsion percentage (the percentage of solids present) and the granulometry of the soil itself as Rhoplex™ molecules surround and attach to coarser particles of sand and within pores, creating a cohesive network.¹⁸⁹ Ultimately the soil in use affects success of the Rhoplex™ amendment in improving water resistance and strength.

¹⁸⁸ Houben and Guillaud, 89; Dickensheets, 56.

¹⁸⁹ Dickensheets, and Matero, 12.

The material characterization of the red and brown soils at FOUN revealed that the red soil from Tecolote, NM currently in use at the site is a poor choice as it is a non-plastic or non-cohesive soil. Soil with non-cohesive properties have lower liquid limits which means the amount of water they can absorb before failing is low. This is a critical consideration at a vulnerable earthen ruin that partially relies on the shelter coat to protect the original adobe substrate. The brown soil from Watrous, NM displayed high liquid and plastic limits, and the addition of sand decreased the levels of shrinkage compared to shrinkage in its raw state. The raw brown soil displayed a high clay content of non-swelling clays which helps the soil bind and remain cohesive. Too high of a clay content can increase shrinkage, in soils, yet if there is too low a clay content then a soil mortar will not bind together properly.¹⁹⁰ The addition of sand to the brown soil created an optimal particle size distribution that decreased shrinkage without compromising its plasticity. Its color also appears to be a better match to the original adobes on site.

Performance tests conducted on the brown soil and sand shelter coats revealed that the higher percentage of Rhoplex™ E-330 (14% solution) had greater resistance to erosion, but displayed lower flow or consistency and lower desorption rates. The shelter coats amended with 7% Rhoplex™ displayed moderate flow, yet also displayed relatively low desorption rates. Both Rhoplex™ amended shelter coats displayed high levels of erosion resistance and water repellency. Percentage of Rhoplex™ did not greatly impact shrinkage of the soils as has been revealed in past research. Continued and long-term testing and research is needed both in the field and in the laboratory on site specific soils to confirm the effects of varying percentages of Rhoplex™ E-330 on soils.

¹⁹⁰ *Ibid.*

Section 8: Site specific recommendations and future research

Previous research has suggested that a sandy soil (60-65% coarse sand, with 10-15% clay content) performs best with Rhoplex™ E-330.¹⁹¹ Even with the addition of sand, the brown soil from Watrous, NM does not meet these minimum suggestions. Yet, the brown soil exhibited greater performance than the red soil from Tecolote, NM. An immediate suggestion for FOUN is to revert to the use of the brown soil or a soil of similar composition and increase the percentage of added fine sand assuming Rhoplex™ continues to be added. Regarding the percentages of Rhoplex™ E-330, field testing should be conducted before any changes are considered on site.

This research recorded observations about application methods of the shelter coats at Fort Union. FOUN and other earthen sites could benefit from a study dedicated to applications of shelter coating. Potential methods for study are application by hand with a rubber glove (as is the practice at FOUN), by hand with a natural material glove (such as sheepskin), by brush (as is the practice at Pecos National Historical Park), or by trowel. Exploring application by pressurized spray using a nozzle is also a worthwhile area of exploration, although the current shelter coat mix used at FOUN is too thick to be applied in this manner. This is an area worthy of future research.

Environmental concerns exist regarding synthetic resins. Research regarding synthetic resins and their impact on the environment is a worthwhile study given the reliance on these products at earthen sites throughout the Southwestern U.S. Spalled and removed shelter coats containing Rhoplex™ E-330 are eventually disposed of at a site nearby the park. It would be worthwhile to study the effects Rhoplex™ E-330 is having

¹⁹¹ Hartzler, "A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites," 97.

on the soil on site, and at the disposal site as they are sources of microplastic contaminating the environment.

Organic additives are another area of research that the study of shelter coats could benefit from. Fort Selden tested organic coatings in the 1990s Fort Selden Test wall experiment. The walls with organic coatings held up poorly to weather, deteriorating almost as quickly as unamended shelter coats.¹⁹² The final Fort Selden report recommended further research into both synthetic resins and other chemical products, as well as traditional or organic additives. The results of the Fort Selden tests describe linseed and other organic additives performing as poorly as unamended soils, suggesting that significant research into organic or natural amendments is required before use at historic sites.¹⁹³

Ultimately the conservation of earthen sites has evolved significantly over the last thirty-five years, yet there is much to be explored and published about the practice of shelter coating. This thesis is a crack in the ceiling of research that will be uncovered through future study of the practice of shelter coating as a preventive conservation method for earthen sites.

¹⁹² Oliver, *Fort Selden Adobe Test Wall Project: Phase I: Final Report*, 24.

¹⁹³ *Ibid.*

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Appendices

Appendix A: Fort Union National Monument Shelter Coat Spall Field Analysis

HSR #	Site Name	Room Number	Cardinal Direction of Wall Face	Date of Last Shelter Coating (SC)	SC Layers	SC Thickness	Separation?*	Cracking/other failure	Notes
32	Clerk's Quarters	3, Exterior	South	2021	5	1 3/8"	Yes	Yes/Adobe loss with SC spall	-
		3, Interior	North	2021	3	1"	Yes	Yes/Adobe loss with SC spall	-
		4, Interior	North	2021 (Lower)	2	3/4"	Yes	Yes/Significant spall across entire upper and lower wall	-
		4, Interior	South	2020	2	3/8"	Yes	Yes on 2021 SC	Spall occurring on 2020 coat directly next to 2021
		1, Interior	North	2021	5	3/8"	Yes	Yes/Significant spall across entire wall	-
		1, Exterior	North	2021	4	1"	Yes	Yes/Significant spall across entire wall	-
43	Commissary Storehouse	2, Interior	North	2021	-	-	-	No	Minor spall on North upper left, too high to measure thickness etc.
42	Storehouse	3, Exterior	North	2020-2021?	-	-	-	No	Minor spall on North upper left, too high to measure thickness etc.
41	Storehouse	1, Interior	North	2021?	3	1"	Yes	Yes significant map cracking across entire wall	-
40	Storehouse	2, Exterior	South	2021		1"	Yes	No	Example of 2019, 2020 and 2021 mud SC on one wall
		2, Interior	North	2020	3	2"	Yes	Yes	Good example of same wall different SC layers
		2, Interior	North	2020	5	1.5"	Yes	Yes	Good example of same wall different SC layers

HSR #	Site Name	Room Number	Cardinal Direction of Wall Face	Date of Last Shelter Coating (SC)	SC Layers	SC Thickness	Separation?*	Cracking/other failure	Notes
39	Storehouse	3, Interior	North	2021	2	1.5" (Coat 1: 1", Coat 2 surface: 1/2")	Yes	Yes	Example of individual coat thicknesses
		4, Exterior	South	2021	4	1.5" (Coat 1: 1/2", Coat 2 surface: 1")	Yes	No	Not recorded by NPS as having been coated in 2021
		4, Exterior	South	2021	2	1/4"	Yes- Shelter coat (SC) from SC separation	No	-
36	Mechanics	31, Interior	South	2021?	3	1"	Yes	Yes/Adobe loss with SC spall	Inbetween rooms 31 and 32 on map
		11, Exterior	East	2021	3	1.5"	Yes	Yes	-
		27, Exterior	North	2021?	2	1/2"	No	Yes	-
		31, Interior	East	2021?	-	-	-	Yes/Significant spall across entire upper wall	Too high to measure thickness etc.
57	Hospital	3-4 East Façade, Exterior	East	2021	-	-	-	-	Too high to measure thickness etc., SC applied September 2021 and spalling is already evident across upper
		2, North	North	2021	1	1/4"	No	No	Very sandy SC mix
		2, North	North	2021	1	1/4"	Yes- SC from SC separation	Yes	Very sandy SC mix
							*Separation recorded between historic adobe and shelter coat unless otherwise specified		

Appendix B: Laboratory Testing Matrix

Test	Property Measured	Standard Referenced	# of Composites	Size of samples	Equipment	Materials	Testing Time Required	Notes	Status
Confirmatory Soil Tests									
Particle Size Analysis (Wet Sieve)	Analysis of fines	ASTM D7928-21e1 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, Lab 15 Penn ACL	2	Based on particle size, 50-200g after drying	Standard sieve set, Washing Sieve and mesh, Designated separating sieve, washing sink/spray nozzle, Balances, Sieve containers (weighing boats?) specimen containers, transfer container, cumulative mass container, sieve brushes	Dry aggregate (mass) of red and brown soils, distilled water	7-14 Days	Other related tests: ASTM D6913M-17 (Includes wet sieving process for fines) and D1140-17 Standard Test Methods for Determining the Amount of Material Finer than 75-µm (No. 200) Sieve in Soils by Washing (1140 used by Dickensheets)	Complete
Particle Size Analysis (Dry Sieve)	Analysis of fine and coarse aggregates/gradation or particle size distribution	ASTM D7928-21e1 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, Lab 15 Penn ACL	2	Based on particle size, 50-200g after drying	Balances, Sieve, Oven	Dry aggregate (mass) from red and brown soils	1-2 Days	Dry sample for 24 hours before sieving, this test is conducted on everything that did not pass the 75 micron sieve in the wet sieve process.	Complete

Liquid and Plastic Limits (Atterburg Limits)	Plasticity index	ASTM D4318-17e1, Lab 16 Penn ACL	9	LL: 150-200g passing No. 40 sieve, PL: 20g	LL: Liquid Limit Device (Casagrande), flat grooving tool, height gauge, water content containers, balance, mixing and storage dish. PL: Ground glass plate for rolling, spatula, no40 and no10 sieves, wash bottle, drying oven, washing pan	Red and brown soils, Distilled water, sand, Rhoplex E-330	1-2 days	Test was run on the red and brown raw soils, then on the red and brown soils with sand added, THEN the test was run again on the brown soil + sand with 14% Rhoplex E-330 and separately with 7% Rhoplex E-330	Complete
Salt Concentration	Amount and Type of Salt Present	WAAC Newsletter 2011 and GCI Lab Session on Salt Analysis, Dickensheets Thesis	2	20g	EM Quant Strips or Merck Indicator Strips	Red and brown soils, Distilled water	1 Day	Can run this test during other soil testing	Complete
pH Test	pH levels affecting stability of clay minerals in soil	ASTM D4972-19, Standard Test Methods for pH of Soils, Dickensheets Thesis referenced	2	20g	pH paper, balance, No. 10 sieve, 100-250 mL glass beaker, volumetric flask, thermometer	Distilled water	1 Day	pH test strips in the lab	Complete
Carbonate Content	Carbonate (acid-soluble) content	ASTM D4373-21 Rapid Determination of Carbonate Content of Soils/ See Dickensheets adaptation of gravimetric mortar analysis	2	30g	drying oven, balance, mortar and pestle	Red and Brown Soils, Hydrochloric Acid, Distilled water	2 Days	Can run this test during other soil testing	Complete

Methylene Blue Adsorption test	Clay minerology	This test is loosely based on the French standard AFNOR NF P 94-068-1998 that has been modified slightly for use with similar quantities	2	60 g	Methylene blue powder, solution prepared a few days in advance of the test, 40cm filter paper	Red and Brown Soils	1 day	Dickensheets, Iyer theses- "This test is loosely based on the French standard AFNOR NF P 94-068-1998 that has been modified slightly for use with similar quantities."	Complete
TOTAL # of Composites			21						
Shelter Coat and Adobe Mixing Standard									
Shelter Coat Formulas	Sufficient mixing of soils to make shelter coat coupons	ASTM C305-14 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency; Laboratory Manual for Architectural Conservators (Teutonico)	-	-	Hobart mixer C-100	Unamended optimal soil, Rhoplex E-330 amended soil, amended soil with lower concentration of e-330	5-7 days or until thoroughly dried	Shelter coat formulas were spread at 1/4" thick on adobe disks by hand and were left to dry on lab mats covered with paper towel (asorbant), and they were covered with wet (wrung out) burlap for 24 hours and then left to dry.	Complete
Adobe Disks	Sufficient mixing of soils to make adobes	ASTM C305-14 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency;	60 adobe disks were made, full adobe bricks from FOUN remain in the lab	-	Hand mill grinder, Hobart mixer C-100	Crushed adobe block, Water	5-7 days or until thoroughly dried	Full adobe bricks from FOUN were broken apart with a hammer, ground through the hand mill in the lab and then re-shaped into	Complete

		Laboratory Manual for Architectural Conservators (Teutonico)						adobe disks. The adobe disks were left to dry on lab mats covered with paper towel (asorbant), and they were covered with wet (wrung out) burlap for 24 hours and then left to dry.	
Performance Tests on Shelter Coat Formulations*								*3 Formulations were tested: Unamended Brown soil + sand, 14% Rhoplex E-330, 7% Rhoplex E-330)	
Consistency	Semifluid consistency	C230/C230M-21, Standard Specification for Flow Table for Use in Tests of Hydraulic Cement,” (West Conshohocken, PA: ASTM 2014), FOR CALCS: ASTM C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar	6	Mass per test based on flow mold fill	Flow mold	Unamended optimal soil, Rhoplex E-330 amended soil, amened soil with determined additive	1 day	Wear earplugs when using the flow table	Complete
Shrinkage	Qualitative shrinkage	ASTM C1148-92a Standard Test Method for Measuring the Drying Shrinkage of Masonry Mortar (withdrawn 2019 but no updated	15	Mass per test based on samples using glazed and unglazed saucers	Unglazed terracotta saucers, trowel	Brown soil, sand Rhoplex E-330 amended soil, distilled water	Approximately 3 days or until samples are thoroughly dry	Unglazed saucers were soaked in water for 24 hours before testing. Shelter coat formulations were then troweled into	Complete

		version is available on ASTM) (also reference ASTM C157 length change of hardened hydraulic-cement mortar)						the saucers to the edge of the lip (NOT over the lip) and were covered with wet (wrung out burlap) for 24 hours and then left to dry.	
Wet/Dry	Effect of 48 hour wet-dry cycle	ASTM D 599M-15 Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures	15	Mass per test based on g per thickness and composite	Deionized water, oven, scale	Brown soil, sand Rhoplex E-330 amended soil, distilled water	12 cycles	Durability Test, Modify test to exclude physical abrasion (Dickensheets thesis)	Not conducted
Freeze/Thaw	Stability of sample under freeze-thaw conditions	ASTM D 560M-16 Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures	15	Mass per test based on g per thickness and composite	Deionized water	Brown soil, sand Rhoplex E-330 amended soil, distilled water	12 cycles	Durability Test, Modify test to exclude physical abrasion (Dickensheets thesis)	Not conducted
Measuring Surface Water Permeability	Water vapor permeability	ASTM E96M-16 Standard Test Methods for Water Vapor Transmission of Materials	15	Mass per test based on g per thickness and composite	Plastic containers, deionized water, dessicant	Brown soil, sand Rhoplex E-330 amended soil, distilled water	Standard	Declet thesis used desiccant method (astm e96m)- In such method, the specimens is sealed against a tri-cornered beaker filled with water. The assembly is placed in a controlled atmosphere, and the assemblies are weighed periodically to measure the rate of water vapor movement through the	Not conducted

								specimen and into the desiccant.	
TOTAL # of Composites			66						
Adobe Mock Up Tests (Shelter Coats on Adobe Disks)*								*3 shelter coats formulations were tested after drying on adobe disks: Unamended Brown soil + sand, 14% Rhoplex E-330, 7% Rhoplex E-330)	
Water Drop Absorption (Microdrop)	Absorption and desorption rates	UNESCO, Rilem developed test referenced from Laboratory Manual for Architectural Conservators (Teutonico)	3	Test conducted 3-5 times on different spots on one sample of the shelter coat formulations	Oven, dessicator, buret, deionized water	Shelter coats on adobe disks, deionized water	1 Day	Samples can be reused	Complete
Water Drop Erosion	Depth of erosion	CRAterre developed test referenced from Zinn thesis	15	Test conducted 3-5 times on the shelter coats	Burrets, ring stands and clamps, plastic containers, circular prisms to hold shelter coats in place	Shelter coats on adobe disks, deionized water	1-2 Days	Durability Test, this test is destructive- the samples cannot be reused	Complete
TOTAL # of Composites			18						
TOTAL # of Composites all Tests			105						

Appendix C: Fort Union Consolidated Treatment History

Commercial Name	Phase of Use at FOUN*	Chemical Family	Chemical Class	Manufacturer	Chemical Properties	Solvent	Physical Properties	Application Method (if known)
DC 129G	Phase 1	Synthetic Resin	Resin	Dow Corning	Thermoplastic resin, organic	Xylene	Formulated as a water repellent in the mid 1950s, insoluble in water	-
Dehydratine 22	Phase 1	Synthetic Resin	Silicone	Horn Corporation (Tamms Industries),	3% silicone	Unknown, likely non-water based such as kerosene	Water repellent	-
Silaneal 772/DC-772	Phase 1 and Phase 2	Synthetic Resin	Silicone (Sodium Methyl Siliconate)	Dow Corning	Silicones penetrate the substrate, as such the substrate should be pH neutral to 10	Water-based solvent	Water-dilutable so it provides water repellency on a variety of substrates while allowing water vapor to pass	Spray applied
Daracone	Phase 1 and Phase 2	Synthetic Resin	Silicone	Dewey and Almy	5% silicone	Kerosene or non-water based solvent	Waterproofing compound but ultimately allowed water to pass	Brush applied
Hydrocide SX Colorless	Phase 1 and Phase 2	Synthetic Resin	Silicone	Sonneborn, LLC	5% silicone	Mineral Spirits	Water repellent	-
Klear-Film	Phase 2	Synthetic Resin	Silicone	N/A	Unknown	Unknown	Water repellent	-
DC-770	Phase 2	Synthetic Resin	Silicone (monomethyl dimethyl silconate)	Dow Corning	Unknown	Mineral Spirits	Water repellent	-
Hydrocide Colorless 101	Phase 2	Synthetic Resin	Silicone	L. Sonneborn and Sons Inc.	Unknown	Not water based, additional information unknown	Water repellent	Brush applied
Polystyrene	Phase 2	Synthetic Resin	Plastic	Dow Chemical	Polyaddition Resin, thermoset, plastic is a chemically derived synthetic blend of one or more types of polymers	Benzol	Rigid and transparent, undergoes considerable shrinkage, water resistant	-

Pencapsula	Phase 2 and 3	Synthetic Resin	Epoxide, Polyurethane,	Texas Refinery Corporation	Polycondensate resin, thermoset	Petroleum-based solvents: TRC-150, paint thinner, kerosene, or clear oil fuel	Created an impervious layer upon application, Epoxy resins create products with exceptional toughness, adhesion and chemical resistance, penetrates the substrate	Spray applied at maximum PSI with high-pressure sprayer
Sandstone and Adobe Coating	Phase 3	Synthetic Resin	Epoxide	Texas Refinery Corporation	Polycondensate resin, thermoset	TRC-150, Kerosene	Formed a coating that trapped moisture, precursor to Pencapsula	-
Silexore	Phase 3	Synthetic Resin	Silicone	J.W. Rylands Co.	Unknown	Unknown	Unknown	-
Methyl methacrylate and 2% Ethylene glycol dimethacrylate	Phase 3	Synthetic Resin	Polymethyl methacrylate (PMMA)	Unknown	Polycondensate resin, thermoset	Unknown	Unknown	-
Water Emulsion Pencapsula	Phase 3	Synthetic Resin	Epoxide	Texas Refinery Corporation	Polycondensate resin, thermoset	Emulsified in water	Similar to Pencapsula	Spray applied
Unamended Soil Shelter Coats	Phase 4	-	-	-	-	-	-	-
Daraweld-C	Phase 5	Synthetic Resin	Polyvinylacetate	GCP Applied Technologies	Polymer & Vinylacetate-dibutylmaleate copolymer dispersion in water	Emulsified in water	Bonding agent	-
Rhoplex™ E-330	Phase 5	Synthetic Resin	Acrylic Polymer Emulsion	Dow	Polyaddition Resin, thermoplastic	Emulsified in water	Improves bond to the substrate, soil imparts properties to the acrylic	Mixed into soil and applied by hand using rubber gloves

*Phases of Use at FOUN:
 Phase 1: 1956-1958
 Phase 2: 1959-1962
 Phase 3: 1963-1980
 Phase 4: 1981-2000
 Phase 5: 2000-2022

Appendix D: Hydrometer Calculations and Analysis

Sedimentation Test: Raw BROWN Soil Fort Union National Monument																								
Date	Time	Elapsed Time (mins) T	Temp Correction (Ct)	Solution Temp Celcius	Actual Hydrometer Reading (ra)	A	B	Meniscus Correction (Cm)=(B- A)X1000	True Hydrometer Reading (R) = Ra - Cm (Meiscus correction only)	Dispersing Agent Correction (x)	Effective Depth L (cm) from Table 4	Effective Depth L/Elapsed Mins T	Sq. Root of L/T	Assumed Unit Weight of Solids (Gs)	K (Table 3)	D(mm)	D(um)	Corrected Reading, Rc=Ractual-zero correction x+Ct	Correction Factor unit weight of solids, a	Original Weight of Soil in Suspension (Ws)	% Finer = Rcorrected (unit weight solids correction)/ Ws x100	% Clay	Notes	
25-Mar	12:12pm	0.5	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		*silts are between 0.003 to 0.0625 or 3.9 to 62.5 microns	
25-Mar	12:13pm	1	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	12:14	2	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	12:16pm	4	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	12:20pm	8	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	1230pm	15	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	1245pm	30	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	115pm	60	0.2	21	>60	0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
25-Mar	215pm	120	0.2	21	56	0	0.001	1	55	6.8	7.3	0.06083333	0.24664414	2.7	0.0133	0.00328037	3.280367	49.4	0.99	180.1	27.1549139	27% Clay	*clays are between 0.001 to 0.0039 mm or 1- 3.9microns)	
25-Mar	415pm	240	0	20	48	0	0.001	1	47	6.8	8.6	0.03583333	0.18929694	2.7	0.0134	0.00253658	2.536579	41.2	0.99	180.1	22.6474181	clay		
25-Mar	815pm	480	0	20	45	0	0.001	1	44	6.8	9.1	0.01895833	0.13768926	2.7	0.0134	0.00184504	1.845036	38.2	0.99	180.1	20.9983343	clay		
26-Mar	11am	1380	0	20	42	0	0.001	1	41	6.8	9.6	0.00695652	0.08340577	2.7	0.0134	0.00111764	1.117637	35.2	0.99	180.1	19.3492504	clay		
26-Mar	8pm	1860	0.2	21	37	0	0.001	1	36	6.8	10.4	0.0055914	0.07477565	2.7	0.0133	0.00099452	0.994516	30.4	0.99	180.1	16.7107163	clay		
28-Mar	11am	4200	0.2	21	23	0	0.001	1	22	6.8	12.7	0.00302381	0.05498918	2.7	0.0133	0.00073136	0.731356	16.4	0.99	180.1	9.01499167	clay		
29-Mar	12pm	5700	0.2	21	22	0	0.001	1	21	6.8	12.9	0.00226316	0.04757266	2.7	0.0133	0.00063272	0.632716	15.4	0.99	180.1	8.46529706	clay		

Sedimentation Test: Raw RED Soil Fort Union National Monument																								
Date	Time	Elapsed Time (mins) T	Temp Correction (Ct)	Solution Temp Celcius	Actual Hydromet er Reading (ra)	A	B	Meniscus Correction (Cm)=(B-A)X1000	True Hydromet er Reading (R) = Ra - Cm (Meiscus correction only)	Dispersing Agent Correction (x)	Effective Depth L (cm) from Table 4	Effective Depth L/Elapsed Mins T	Sq. Root of L/T	Assumed Unit Weight of Solids (Gs)	K (Table 3)	D(mm)	D(um)	Corrected Reading, Rc=Ractual-zero correction x+Ct	Correction Factor unit weight of solids, a	Original Weight of Soil in Suspension (Ws)	% Finer = Rcorrected (unit weight solids correction)/Ws x100	Clay or silt?	% Clay	Notes
25-Mar	12:12pm	0.5	0.2	21	>60		0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		*silts are between 0.003 to 0.0625 or 3.9 to 62.5 microns
25-Mar	12:13pm	1	0.2	21	>60		0	0.001	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		
25-Mar	12:14	2	0.2	21	57	0	0.001	1	56	6.8	7.1	3.55	1.88414437	2.7	0.0133	0.02505912	25.05912	50.4	0.99	137.49	36.2906393	silt		
25-Mar	12:16pm	4	0.2	21	51	0	0.001	1	50	6.8	8.1	2.025	1.42302495	2.7	0.0133	0.01892623	18.92623	44.4	0.99	137.49	31.9703251	silt		
25-Mar	12:20pm	8	0.2	21	46	0	0.001	1	45	6.8	8.9	1.1125	1.05475116	2.7	0.0133	0.01402819	14.02819	39.4	0.99	137.49	28.3700633	silt		
25-Mar	1230pm	15	0.2	21	41	0	0.001	1	40	6.8	9.7	0.64666667	0.80415587	2.7	0.0133	0.01069527	10.69527	34.4	0.99	137.49	24.7698014	silt		
25-Mar	1245pm	30	0.2	21	38	0	0.001	1	37	6.8	10.2	0.34	0.58309519	2.7	0.0133	0.00775517	7.755166	31.4	0.99	137.49	22.6096443	silt		
25-Mar	115pm	60	0.2	21	35	0	0.001	1	34	6.8	10.7	0.17833333	0.42229532	2.7	0.0133	0.00561653	5.616528	28.4	0.99	137.49	20.4494872	silt		*clays are between 0.001 to 0.0039 mm or 1-3.9microns)
25-Mar	215pm	120	0.2	21	32	0	0.001	1	31	6.8	11.2	0.09333333	0.30550505	2.7	0.0133	0.00406322	4.063217	25.4	0.99	137.49	18.2893301	silt	18% clay	
25-Mar	415pm	240	0.2	21	30	0	0.001	1	29	6.8	11.5	0.04791667	0.21889876	2.7	0.0133	0.00291135	2.911353	23.4	0.99	137.49	16.8492254	clay		
25-Mar	815pm	480	0.2	21	25	0	0.001	1	24	6.8	12.4	0.02583333	0.16072751	2.7	0.0133	0.00213768	2.137676	18.4	0.99	137.49	13.2489636	clay		
26-Mar	11am	1380	0.2	21	20	0	0.001	1	19	6.8	13.2	0.00956522	0.09780193	2.7	0.0133	0.00130077	1.300766	13.4	0.99	137.49	9.64870172	clay		
26-Mar	8pm	1860	0.2	21	19	0	0.001	1	18	6.8	13.3	0.00715054	0.08456085	2.7	0.0133	0.00112466	1.124659	12.4	0.99	137.49	8.92864936	clay		
28-Mar	11am	4200	0.2	21	16	0	0.001	1	15	6.8	13.8	0.00328571	0.05732115	2.7	0.0133	0.00076237	0.762371	9.4	0.99	137.49	6.76849225	clay		
29-Mar	12pm	5700	0.2	21	14	0	0.001	1	13	6.8	14.2	0.00249123	0.0499122	2.7	0.0133	0.00066383	0.663832	7.4	0.99	137.49	5.32838752	clay		

Appendix E: Water Drop Absorption (Microdrop) Results

Sample	Absorption time into treated surface (tx)	Absorption time into untreated surface(tn)	Evaporation or desorption time on the sample surface (d)	Temperature and humidity during experiment
A. Unamended	-	0 seconds (immediate)	660 seconds	21.2°C, 31% humidity
B. 7% Rhoplex™	18 seconds	-	801 seconds	
C. 14% Rhoplex™	279 seconds	-	1142 seconds	

Microdrop round 1

Sample	Absorption time into treated surface (tx)	Absorption time into untreated surface(tn)	Evaporation or desorption time on the sample surface (d)	Temperature and humidity during experiment
A. Unamended	-	0 seconds (immediate)	600 seconds	21.2°C, 31% humidity
B. 7% Rhoplex™	17 seconds	-	928 seconds	
C. 14% Rhoplex™	325 seconds	-	1320 seconds	

Microdrop round 2

Sample	Absorption time into treated surface (tx)	Absorption time into untreated surface(tn)	Evaporation or desorption time on the sample surface (d)	Temperature and humidity during experiment
A. Unamended	-	0 seconds (immediate)	510 seconds	21.2°C, 29% humidity
B. 7% Rhoplex™	15 seconds	-	960 seconds	
C. 14% Rhoplex™	266 seconds	-	1260 seconds	

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