2019

A Performance Evaluation of Amended Stabilization Mortars at Wupatki National Monument, Arizona

Caroline Dickensheets

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A Performance Evaluation of Amended Stabilization Mortars at Wupatki National Monument, Arizona

Abstract
Earthen mortars are commonly amended to display ‘improved’ performance and weathering properties than unamended soil mortars. In an effort to make more lasting repairs, the National Park Service (NPS) has used amended earthen mortars on their historic structures since the 19th century. These interventions have displayed various levels of compatibility with original masonry material. One such amendment, the acrylic emulsion Rhoplex™ E-330, has been used in setting and pointing mortars for the conservation of ruin sites at multiple National Parks since the 1970s. This paper focus on conservation repair mortars, specifically the durability and performance of amended earthen mortars at the Wupatki Pueblo. Located in north-central Arizona, near Flagstaff, Wupatki National Monument consist of multiple sites with the Wupatki Pueblo dating to ca. 1100 AD. Built upon a natural outcropping, the pueblo is constructed of coursed rubble stone, predominately of the local Moenkopi sandstone, all laid in an earthen mortar. Since 1924, the monument has been administered by the National Park Service with restoration and stabilization work continuing to today.

This research examines conservation soil-based mortars at archaeological sites with Wupatki Pueblo serving as the case study. Research includes analyzing and characterizing the composition of past and current stabilization mortars used on site, assessing their overall compatibility with the masonry, and creating test formulations to provide recommendations for future use. Test formulations evaluate the effects of acrylic polymers on Wupatki's current soil supply with only the ratio of Rhoplex™ E-330 to water altered in each formulation. Physical and mechanical tests performed on these mortar formulations provide insight into how these mortars perform in the field. Ultimately, these efforts provide the NPS with an optimal amended stabilization mortar formulation that is compatible with the Wupatki Pueblo's original masonry system.

Keywords
earthen, mortar, amended, Rhoplex, acrylic

Disciplines
Historic Preservation and Conservation

Comments
Suggested Citation:
A PERFORMANCE EVALUATION OF AMENDED STABILIZATION MORTARS AT WUPATKI NATIONAL MONUMENT, ARIZONA

Caroline Dickensheets

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2019

Advisor & Program Chair
Frank G. Matero
Professor of Architecture and Historic Preservation
Acknowledgements

Special thanks to my thesis advisor and program director, Professor Frank G. Matero for his support throughout this research and the opportunity to work at Wupatki and multiple other sites out west.

Special thanks to Courtney Magill for flying out to the site with me, climbing on top of the Wupatki Pueblo walls to complete my condition assessment, and her ongoing support throughout this research project.

Thanks to the Flagstaff Area National Monument’s staff. In particular, Ian Hough for all his help coordinating our site visit and acquiring materials and Dana Brown for helping us navigate the pueblo walls and collecting my samples.

Thanks to Dennis Pierattini and all of the staff at the Fabrication Lab for your continuous support throughout the semester and keeping me company during spring break.

Thanks to Dr. Alex Radin, for your assistance with the mechanical tests at the Laboratory for Research on the Structure of Matter as well as Steve Szewczyk for his guidance through the XRD analysis.

Thanks to Sara Stratte and Dorcas Corchado for lugging those gallon sized bags of wet soil back from Arizona so that I could complete my laboratory testing.

Lastly, thank you to my parents for their encouragement and continuous support of all my endeavors.
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Section 1: Introduction

1.1 Project Purpose

Located in north-central Arizona, near Flagstaff, Wupatki National Monument encompasses an area of 35,254 acres containing the remnants of several Ancestral Sinaguan villages, shrines, farmlands, and other associated cultural landscape features. Wupatki Pueblo, the largest of the extant villages, most likely dates to ca. 1100 although occupation stretches back earlier to ca. 500 AD. Since 1924, the Monument has been administered by the National Park Service (NPS) with preservation work continuing annually. Built upon a natural rock outcropping, the pueblo is constructed of coursed rubble stone, predominately of the local Moenkopi
sandstone with some basalt, all laid in an earthen mortar (Figure 1). The current research focuses specifically on the North and South Units of the Pueblo.

In an attempt to make repairs to excavated masonry rooms last longer, the NPS has used amended mortars both at Wupatki and other precontact (prehistoric) sites across the Southwestern United States since the late 19th century. Amendments were first added to soil mortars during stabilization work at Casa Grande in 1889.¹ This research examines conservation repair or ‘stabilization’ mortars for archaeological sites, specifically the durability and performance of acrylic amended soil or earthen mortars at Wupatki Pueblo. Amended earthen mortars are employed for greater durability and weather resistance than the soil mortars originally used. One amendment, the acrylic emulsion Rhoplex⁴ E-330, has been used by NPS for over 40 years and is reported to have varying success depending on the soil type (granulometry and clay mineralogy) and the percentage of amendment.²,³ Although lab and field tests have been conducted using a range of acrylic amendments in type and concentration at different parks across the Southwest, there is insufficient data to substantiate anecdotal evidence about its performance over time in the field. Quantitative knowledge about the effects of this acrylic amendment on soil mortar performance can be gained by creating carefully gauged Rhoplex modified mortar formulations with Wupatki’s current stabilization soil supply and subjecting it to laboratory testing.

This research will assist the Flagstaff Area National Monuments in developing best practices in the cyclical maintenance of their masonry sites. The study can also help inform visitors about site conservation and current preservation activities within the Monument boundaries. As part of a larger CESU (Cooperative Ecosystem Studies Unit) task agreement, this study addresses cultural heritage resource issues at multiple scales. Beyond the immediate site, this thesis will contribute toward developing a framework and methodology for formulating and assessing earthen mortars for masonry sites at parks across the Southwest.

1.1.1 Approach to Preservation at Wupatki National Monument

Wupatki National Monument uses a values-based approach for preservation management of the five precontact sites within the Monument—Wupatki Pueblo included. These values determine the appropriate preservation strategies employed and are described in the annual preservation reports as follows:

1. Location and Setting—physical placement of the site, relation to surrounding landscape
2. Design, Workmanship, and Materials—spatial layout of site, technical/artistic construction skill expressed in masonry walls, local building materials
3. Socio-Cultural Association—connections with modern Pueblo practices and indigenous Native American cultural groups
4. Feeling—sense of connection with the past

In addition to these identified values, preservation methodology at Wupatki National Monument is guided by a comprehensive Ruins Preservation Plan and Implementation Guidelines. These

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guidelines highlight five objectives used to conduct preservation at multiple sites within the Wupatki NM:

1. Ensure that all identifiable original fabric is protected from further deterioration and preserved in a manner that perpetuates the inherent construction style and patterning.
2. Complete all physical treatments in a manner that continues the existing appearance of the architectural remains.
3. Ensure that the mass, scale, and proportion of the existing architectural remains are maintained.
4. Ensure the existing physical layout is maintained.
5. Ensure that all materials used in the treatment process will be visually and structurally compatible with the original architecture in terms of color, texture, and construction style.

These preservation objectives are hindered by several factors identified in Wupatki’s annual Ruin Preservation Activities Report which are structured into four broad categories:

- **Category 1.** Insufficient funding and labor to deal with the number of resources and their rates of deterioration.
- **Category 2.** Insufficient documentation
- **Category 3.** Past use of unsuitable stabilization techniques and materials
- **Category 4.** Insufficient knowledge concerning agents of deterioration affecting the site

Taking these factors into consideration, preservation activities are generally implemented to mitigate the overall deterioration of the structures and site caused by environmental and human impacts. In relation to the current research, mortar erosion negatively impacts the stability of the original masonry walls allowing other environmental and human impacts to accelerate overall
deterioration and collapse. Immediate preservation work including annual repointing of eroded mortar joints addresses these impacts while continuing historical cycles of maintenance that would have taken place when the pueblo was originally inhabited.

1.2 The Site

1.2.1 Geography

Wupatki National Monument is located in north-central Arizona’s Coconino County, about 41 miles north of Flagstaff. Park boundaries extend east of Arizona Highway 89, with the Coconino National Forest forming the monument’s southern border, and the Navajo Reservation to the east. The Monument may also be accessed through Sunset Crater Volcano National Monument, which is administered along with Walnut Canyon National Monument. These three monuments are collectively referred to as Flagstaff Area National Monuments. Wupatki National Monument was established in 1924 to preserve the thousands of archaeological sites and evidence of past inhabitants of the region. The Wupatki Pueblo is one of multiple sites at the monument and is the largest excavated structure within the park’s boundaries which encompass over 35,000 acres.

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1.2.2 Climate

Wupatki National Monument lies within the Southern Colorado Plateau, an area of arid climate that experiences periods of drought and extended periods of freezing temperatures. This climate zone blankets over the Four Corners region of the American Southwest and encompasses other National Park Service administered sites including Mesa Verde, Bandelier, and El Morro. The National Weather Service Cooperative Observer (COOP) Network station is located in the monument and has been collecting weather data since 1940.

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7 Annual weather data for Wupatki National Monument can be found in Appendix A. Further climate data for Wupatki National Monument including daily summaries can be found through NOAA. Monthly summaries can be accessed through the Western Regional Climate Center which includes average from 1948 to 2006.
The climate of Wupatki National Monument is relatively dry and receives a limited amount of annual precipitation (approximately 8 inches per year). Precipitation is highest in the summer months during monsoon season with an average of approximately 3 inches. However, most of this moisture is lost through evaporation. Winter storms occur from November-March with approximately 6.5 inches of snowfall occurring annually. Temperature varies throughout the year with the warmest temperatures occurring from May-September during which the average daily high temperatures range from 81-95° F. The hottest month on average is July when temperatures average at 95.4° F. The cold season generally occurs from November to February, with average daily highs ranging between 58.3-54.9° F, and then average daily lows ranging between 33.2-29.0° F. Prevailing winds tend to travel from south/southwest to north/northeast with winter winds occasionally shifting from north to south, but prevailing winds traveling southwest to northeast.

Wupatki Pueblo faces many threats due to climate change, including the impact of erratic precipitation events. Intensely powerful storms delivering large amounts of moisture over a short period of time can cause considerable damage to the historic structures and have been occurring with increasing frequency each year. Climate change poses the greatest risk to traditional building materials, soil-based construction (e.g., adobe and soil mortars and plasters). Soil mortars, as a critical component of the masonry wall, are particularly sensitive to water as the soils disassociate and destabilize with excess water. Given Wupatki’s fragmented ruin state its

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8 Western Regional Climate Center, WUPATKI NATL MONUMENT, ARIZONA (029542).
9 Ian Hough, email correspondence, December 10th, 2018.
walls lack the protective architectural features originally in place to combat and control weathering. Due to this susceptibility, weather and climate play a huge role in the survival of masonry laid in earthen mortars. Furthermore, climate change requires taking a predictive approach in planning for how weather patterns will shift in the years to come.

Despite the abundance of climate data collected at Wupatki National Monument, generalizations of climate and weather model data must be reassessed to account for shifting local and regional weather patterns. Ultimately, the increase in extreme weather events, such as heavy bursts of precipitation due to climate change, will stress the earthen mortars and their masonry systems, requiring new approaches to cyclical maintenance and preventive conservation activities.

1.2.3 History

Three prehistoric cultural groups, including the Sinagua, the Cohonina, and the Kayenta Anasazi, occupied the area around Wupatki National Monument. The eruption of the nearby Sunset Crater in 1064 BCE provided favorable agricultural conditions that spurred a migration of inhabitants from across the region. At the height of its occupation in the 12th century, Wupatki Pueblo housed an estimated 120 people making it the largest dwelling in the Sinagua region at the time.¹¹

Although there are approximately 80 excavated and stabilized rooms visible today, at the peak of its occupation, the structure reached a total of approximately 100 rooms. The pueblo is divided into North and South Units that were originally linked through additional rooms and a courtyard area. Its placement on the top of the Moenkopi sandstone outcrop created the

impression that the three-story structure appeared to be over five-stories tall, adding to the prominence of the site.

While the imposing structure deterred any unwanted visitors, a fortified design of the Pueblo’s interior directly addressed security concerns. Originally, solid exterior room walls and segments of free-standing walls enclosed courtyard spaces within the pueblo, allowing for interior movement while limiting direct contact with the exterior. The absence of ground floor doorways further demonstrates this attitude towards controlled access. Instead, roof openings provided the sole entry to ground room floors. Structures outside of the pueblo’s walls include a masonry-lined ball-court, now reconstructed, to the immediate northeast and an unroofed circular room referred to as the “amphitheater”. Depleted soil conditions likely led to the abandonment of the site in the early to mid-13th century.12

Wupatki Pueblo was first observed by Euro-Americans during a U.S. army expedition led by Brevet Captain Lorenzo Sitgreaves in 1851. Although the focus of this expedition was to explore navigable river routes, Sitgreaves had the expedition’s artist, Richard Kern, make a drawing of the ruin. The Pueblo was then visited and described by John Wesley Powell and James Stevenson in 1885 as part of a study of pre-contact (‘prehistoric’) ruins and local tribes by the Department of the Bureau of American Ethnology (Smithsonian Institution). This period of exploration was part of an effort to document native cultures of the American West, however, it is unclear if the group physically visited Wupatki. The first well documented excursion to Wupatki was made by Jesse Walter Fewkes in 1900. Fewkes was the first archaeological investigator of the

He established the first classification scheme for the ruins and several burials. Initially named “Wokoki” by Fewkes, Harold Colton of the Museum of Northern Arizona referred to the site as “Wupatki” in a 1933 publication. The name is a corruption of the Hopi name “Wupakikuh”, which means “Tall House Ruins.”

In 1924, Wupatki National Monument was established through the efforts of Harold S. Colton, J.C. Clarke, and Samuel A. Barrett. This designation did not lead to any immediate preservation efforts, rather the pueblo was guarded by only a handful of caretakers that included the Coltons. Archaeological investigations began on a large scale in the 1930s, but documentation was sparse with no adequate report ever produced. Work was carried out under the direction of the Museum of Northern Arizona with assistance from the United States Government Civil

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14 It should be noted that there is another site within Wupatki National Monument named “Wokoki.” The Wupatki Pueblo is also referred to as NA 405 and the Wupatki Archaeological Survey site number “WS 2676.”
15 Brennan and Downum, 14.
16 A detailed list and history of archaeological and stabilization activities at Wupatki Pueblo can be found in Brennan and Downum’s report Prestabilization Document of Wupatki (2001).
17 Brennan and Downum, 1.
Works Administration (CWA) program. The focus of the 1933-34 excavations was primarily dedicated to preparing the ruins for public visitation, collecting artifacts for the Museum’s collections, and producing work for the unemployed. During this period, many pueblo rooms were excavated, stabilized, and often reconstructed. Upper walls were rebuilt, and roofs were added by the excavators to fit with their interpretation of how the site might have appeared in its peak period of occupation. Modifications to the site helped to facilitate visitor and park personnel access and included safety measures, such as the introduction of steel reinforcing beams, tensioned cables, and doorways. Alterations to the pueblo were extensive enough for early rangers to inhabit some of the excavated rooms (Figure 3).

The second largest archaeological expedition at Wupatki took place in 1952 and included both the excavation and stabilization of rooms for visitation. Insensitive excavation practices and insufficient documentation continued through the 1960s. Only later were NPS policies revised so that reconstructions were reversed, and the pueblo returned to its more ‘as-excavated’ appearance. These initial excavation practices were not only destructive but led to inevitable deterioration once the structures were exposed to the weather.

In 1994, a large effort to document Wupatki’s architecture was initiated by the National Park Service’s Flagstaff Area Monuments and Northern Arizona University researchers. The Wupatki Pre-Stabilization documentation project took place from 1996 to 2000 and a report on the work was authored by Brennan and Downum. This research includes documentation of construction events including mortar types which are further discussed in the Section 3.

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18 Brennan and Downum, 15.
19 Courtney Reeder Jones provides a firsthand account of living in the Wupatki pueblo with her husband as National Park Service caretakers for the site in 1938 in her memoir *Letters from Wupatki*.
1.3 Past Research

1.3.1 Earthen Material

Earthen architecture can survive for hundreds, even thousands of years exposed in dry climates, but it begins to deteriorate when subjected to moisture. The most common source of direct moisture is precipitation such as rain and snow, but moisture can also affect masonry through condensation and rising ground water. Despite the large amount of earthen architectural heritage throughout the world, there is often a lack of knowledge about effective methods to improve the long-term durability of earthen materials and systems. Since the 1950s, and particularly in more recent decades, a renewed interest in earthen architecture has reemerged, largely in connection to sustainable building methods and appropriate technology.

Recent efforts have focused on durability and performance and specifically protection of earthen materials from moisture. \(^{21}\) Additionally, further research has been conducted in relation to the overall geotechnical properties of earthen construction materials.\(^{22}\) The primary focus of this research has been on structural materials such as mud brick and less so on earthen mortars.

1.3.2 Earthen Mortars

Prior to the introduction of calcined binders such as gypsum and lime, soil (clay and sand) mortars were used throughout the world on many building types, attesting to their widespread occurrence and viability. While earthen mortars are typically used with earthen units such as adobe, they are also used in bedding other masonry materials such as brick and stone, as is the


case at the Wupatki Pueblo. This combination of materials requires physical compatibility between the mortar and the stone to create the masonry system. Recent studies into strength optimization of earthen mortars have determined that the effects of reinforcement largely depend on the nature of the soil, its granulometry, and its mineralogical composition.²³

1.3.3 Use of Amended Soil at Archaeological Sites

Originally, earthen mortars presented multiple advantages for early builders in the American Southwest including material abundance, minimal preparation requirements, and durability and effectiveness when properly selected and maintained.²⁴ Although architectural devices and sheltered sites have allowed earthen mortar to remain in good condition, they fail when subjected to moisture. Due to the ruinous condition of most of these sites (most of these structures do not have roofs to shed water), the wall systems are increasingly exposed to weather. Ideally, the earthen mortars at Wupatki Pueblo and countless other sites in the American Southwest would not need amendments. However, due to their exposure to the elements and the Park Service’s need for reduced maintenance, the use of amended earthen mortars is a recent and necessary approach.

The National Park Service has repaired many pueblo ruins and other Ancestral sites with Portland cement mortars since the late nineteenth century, a material now recognized as being physically incompatible with the original masonry systems. Cement mortars are often incompatible with stone masonry systems in performance and appearance. Their impermeability can cause moisture retention within the masonry wall and the stones. As a result, water can

saturate the stone and over time and salts, freeze-thaw cycling, and dissolution can stress the stone causing differential deterioration.

Wet stone is also significantly weaker to dynamic stresses. Cement mortars, though long-lasting, are difficult to repair and replace resulting in layers of irremovable mortar, which end up embedded behind more recent mortar repointing campaigns. Cement mortars are also unsightly. Comparatively, earthen mortars that contain a low amount of cement have been used successfully in some sandstone walls; however the cement’s effect on the color often leads to poor visual matches.\textsuperscript{25}

Other soil amendments popular in the past include asphalt-based stabilizers such as bitumen, calcium aluminate, lime, polyvinyl acetates and aqueous polymer emulsions, such as Rhoplex, which have been used since the 1970s.\textsuperscript{26,27} The latter class of synthetic resin amendments have no impact on soil color, creating a preferable match to the original mortars.

\textbf{1.4 Current Research Methodology}

Research for this study includes the characterization and analysis of Wupatki’s raw materials (soil) and past mortar repairs, as well as the application of standardized testing for new earthen mortars. Because the repair mortar to be studied is soil, testing methods for both soil and mortar have been researched.\textsuperscript{28}


\textsuperscript{27} The most in-depth research specifically related to earthen mortars amended with Rhoplex\textsuperscript{TM} E-330 was written by Robert Hartzler through his thesis research at the University of Pennsylvania which was later published by the National Park Service. This research project largely follows up on the work initiated by Hartzler and applies what is known about Rhoplex\textsuperscript{TM} E-330, soils used at Wupatki NM to make predictions on their performance.

\textsuperscript{28} A detailed research methodology flowchart is in Appendix B.
1.4.1 Site Visit: Conditions Assessment, Collection of Samples

Project fieldwork began with collecting known samples of past and current mortar formulations used over the past 30 years at Wupatki. While in the field, the conditions of these mortars were surveyed. Additionally, constituent materials (soil, sand, water, Rhoplex) used in current preservation mortars were collected and analyzed at the Architectural Conservation Laboratory at the University of Pennsylvania.

1.4.2 Material Characterization

The first series of tests analyzed and evaluated existing stabilization mortars and their components. This includes historic repair mortars and new stabilization mortars. For historic repair mortars, basic observations were made in situ to evaluate previously used repair mortars and their effect on the associated masonry. New stabilization mortars are defined as amended mortars applied in the past five years. They are comprised of either “Nissan Red” (until 2017) or “Moriah” (since 2018) soils with sand added. First, initial analysis of the Nissan Red and Moriah soils was performed to determine their composition. Laboratory analysis then shifted focus to the Moriah soil. Investigations for the presently used formulated soil included particle size distribution (granulometry) both with and without sand, micromorphology, pH, organic content, percent carbonates, salt concentration, and clay mineralogy. Also included in this series was a qualitative salts analysis of the water used in the mortar formulation. This first round of tests allowed for better understanding of the working and final properties of the mortars. In conjunction with the site conditions survey and assessment, mortar performance, durability, and compatibility with the overall masonry system can be deduced.
1.4.3 Mortar Performance Testing

The second series of tests evaluated mortar formulations created in the lab based on the current formulations used on site. By creating fresh samples, it was possible to employ more destructive testing methods. More destructive tests could occur. All prepared test samples used the same soil currently used for stabilization work at the park. Four mortar formulations were tested, the only difference being the percentage of Rhoplex added to each formulation. The control formulation was an unamended soil mortar containing no Rhoplex. The other three formulations include mortars containing either higher or lower ratios of Rhoplex to water (1:7, 1:4, and 1:3 Rhoplex to water by volume). Physical tests performed on the mortars included those measuring consistency, plasticity, shrinkage, water vapor permeability, and durability as wet/dry resistance and freeze/thaw resistance. Mechanical tests included the modulus of rupture and bond/adhesion. This second series of tests on the different mortar formulations provided insight into how these mortars perform in the field and in making recommendations for mortar mixes and applications used at the park for the future.
Section 2: Materials

The original masonry of Wupatki Pueblo was constructed of two materials: Moenkopi sandstone for the stone units and local soils for the mortar. Black basalt stones were selectively used to create horizontal decorative bands in the walls. Since excavation and stabilization, various mortar amendments were used including Rhoplex™ E-330 for enhanced durability. All three of these materials—sandstone, soil and Rhoplex—are discussed in this section.

2.1 Moenkopi Sandstone

The red sandstone at Wupatki National Monument originates from the Triassic Moenkopi Formation which includes sandstone, siltstone, and shale. The Moenkopi formation is comprised of multiple members and strata, each displaying their unique characteristics. The geological formation extends across the American Southwest with the Wupatki Member running through...
northern Arizona and is distinct in its characteristic red to reddish brown color (Figure 4).\textsuperscript{29} Sinagua Indians used the Moenkopi sandstone as the building units for their multi-storied pueblos that largely rested on bedrock. By constructing their villages on rock outcrops, they took advantage of the bedrock for their foundations and the natural heating and cooling effects of the rocks. The Moenkopi sandstone easily splits along (rift) and across (grain) its bed, thus producing excellent semi-uniform units for construction and allowing somewhat controlled coursing with stones laid in their natural bed.\textsuperscript{30} Erosion and weathering of the Moenkopi Formation produced soil for the mortar that held these pueblo walls together.\textsuperscript{31}

The rocks of the Moenkopi are generally fine grained and moderately sorted quartzitic sandstone.\textsuperscript{32} After quartz, calcite is the most abundant mineral in the Moenkopi formation and acts as a cementing mineral. Commonly, the calcite cement also contains dolomite. Small quantities of iron in the sediment have oxidized, giving the formation its reddish hue. Overall, the Moenkopi sandstone displays a high level of variability in its physical and mechanical characteristics, which is observed and discussed in Section 3.2. Moenkopi was latter quarried out of Flagstaff by the Arizona Sandstone Co. beginning in the 1880s and was commercially known as Arizona Red. The stone was cut from the quarry and distributed to locations as far away as Los Angeles up until the 1940s.\textsuperscript{33}

\textsuperscript{29} For more information on the Moenkopi Formation and the Wupatki Member, see Edwin D. McKee’s \textit{Stratigraphy and History of the Moenkopi Formation of Triassic Age} (1954).
\textsuperscript{31} J. Graham, “Wupatki National Monument: Geologic Resources Inventory Report,” (Fort Collins: Colorado), June 2011.
2.2 Earthen Mortars

The soil currently used for stabilization mortars is known commercially as “Moriah.”

According to federal policy, natural resources such as soil may not be extracted from the park even for in-house use. As a result, soils are obtained from commercial sources that meet specific criteria (e.g. color, particle size distribution). Due to the limited nature of these supplies, extraction sites can change location over time. Prior to the Moriah soil, a “Nissan Red” source was used. This soil came from an existing stockpile of weathered sandstone fill purchased from a local construction site with the understanding that there were no archeological or cultural sites in proximity to the supply. However, this source has been depleted, leading to the use of a new “Moriah” soil that is believed to have similar characteristics to the Nissan Red. Before use, the soil is sieved through a ¼” screen to sort out debris and larger aggregates. A washed and graded, coarse commercial sand is then mixed with the soil, typically at a ratio of one-part sand to two parts soil by volume.\(^{34}\) The sand helps strengthen the mortar and reduce shrinkage and cracking. It is not added to alter the color or texture of the final mortar. Further characterization and testing results of the Moriah soil are expanded upon in later sections.

2.3 Rhoplex™ E-330 Emulsion

Rhoplex™ E-330 was developed as a Portland cement modifier and bonding agent for the construction industry in the 1960s.\(^{35}\) As an amendment to Portland cement, it is designed to impart superior flexural, adhesive, and impact strengths to concrete in addition to excellent

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\(^{34}\) At present, Quikrete All-Purpose Sand is used for this purpose. This commercial sand meets ASTM C33, Standard Specification for Concrete Aggregates.

abrasion resistance.\textsuperscript{36} Rhoplex can be successfully used in applications such as resurfacing or patching old concrete, in addition to instances of excessive vibration and traffic. Since their introduction, acrylic polymers have found uses in conservation. They have been adopted by the NPS to amend adobe and earthen mortars since the 1970s.\textsuperscript{37} When used in emulsion form in the mixing water, acrylics provide increased durability and cohesion to earthen mortars without changing the color of the soil. If used in low concentrations, they also allow the mortar to weather in a manner similar to unamended mortar. This mode of weathering satisfies the Park Service’s aesthetic requirements to match the original mortars. Past studies have shown that the performance of Rhoplex amended mortars depends not only on the emulsion percentage (percent solids) but on the granulometry of the soil itself.\textsuperscript{38}

Prior to the use of Rhoplex\textsuperscript{TM} E-330, Portland cement was a common stabilization additive for soil mortars used at sites across the American Southwest. Cement has many advantages as a construction material including strength, durability, and low cost. However, the material was used indiscriminately, creating soil mortars and renders physically and aesthetically incompatible with original masonry systems. Portland cement imparts high strength and durability against weathering; however, certain characteristics, such as its high bond strength and low flexural and impact strength, make it incompatible with earthen mortar masonry systems. Although structurally quite durable, soil-cement mortars can be difficult to both repair and replace and are often visually dissimilar to the original mortars. Due to these shortcomings, the

\textsuperscript{36} Robert Hartzler, 1996, \textit{A Program of Investigation and Laboratory Research of Acrylic-Modified Earthen Mortar Used at Three Prehistoric Puebloan Sites} (Master’s Thesis, University of Pennsylvania), 14.
\textsuperscript{37} Hartzler, 18.
\textsuperscript{38} Hartzler, 97.
NPS has experimented with other amendments, including Rhoplex™ E-330. Since acquiring Rohm & Haas Chemicals LLC in 2009, The Dow Chemical Company now produces Rhoplex™ E-330 and supplies the product to the National Park Service for several Southwestern sites including Wupatki National Monument.

Rhoplex™ E-330 is an emulsion consisting of finely dispersed particles suspended in water that coalesce into a tough film during evaporation (Figure 5). Unlike a solution, which is a homogenous mixture formed by dissolving one or more substances, an emulsion is a stable suspension. As an acrylic emulsion and copolymer, Rhoplex™ E-330 is a combination of methyl methacrylate and ethyl acrylate that is dispersed in an aqueous medium. The particles found in Rhoplex™ E-330 are so small (less than 1.0 µm) that Brownian forces keep them in suspension. While curing cement or lime takes many days, Rhoplex™ E-330 dries and polymerizes relatively quickly. Although not soluble in water, the film swells and softens slightly when wet. The assumption is that the material acts as a cohesive binder between the soil particles.

39 The use of cements has been scaled back at many sites due to issues of color, strength, and capillary potential. However, the advantages of reduced maintenance by using these cement modified mortars results in their continued use at many sites. For in depth analysis on cement modified earthen mortars, see William Zinn’s thesis, *Cement Modified Earthen Mortar – An Investigation*.


41 Hartzler, 26.
The Rhoplex™ E-330 product is an opaque, white to off-white liquid that has an ammonia odor. It has a solids content of approximately 47% and is in an alkaline water base. It has a pH of 9.3-10.2, a specific gravity of 1.0-1.2, with melting and boiling points that are the same as water.42 The product can be stored at temperatures between 1-49°C (34-120°F) and should be kept from freezing as product stability may be affected. Rhoplex™ E-330 must be stirred well before use to insure dispersion of the copolymers.43

43 Ibid.
2.3.1 Rhoplex at Wupatki National Monument and the Park Service

Rhoplex has been used throughout the American Southwest for ruins preservation activities since the 1970s. David J. Butterbaugh, a scientist and retired manager from Rohm and Haas, began testing emulsions as applied coatings on adobe after visiting Casa Grande Ruins National Monument. Rhoplex E-330 along with other forms of acrylic were favored due to their colorless effect and durability in outdoor environments and were applied in the form of a spray as an early consolidant to earthen materials. NPS scientist Dr. Dennis Fenn at Chaco Culture National Historic Park also conducted early testing of acrylic dispersions, discovering that they caused little to no change in color to the soils used in the mortars. Additionally, the amendments imparted a low compressive strength and level of permeability to the mortars compatible with the original masonry system. Ultimately, Fenn provided usage criteria that recommended no more than 13% chemical solids by weight (1:2.5, E-330). He also recommended that the soil used should be approximately 70% sand, 20% clay, and 10% (or less) silt. Since Fenn’s research in the 1970s, the use of Rhoplex E-330 has spread throughout the American Southwest at other National Park Service administered ruins, often without considering his full recommendations.

At Wupatki National Monument, Rhoplex E-330 replaced cement as an amendment to earthen mortars in the 1980s and remains the standard today.

44 For further information regarding Butterbaugh’s research, see his field reports with the title “Mud Brick Conservation Project – Field Report” beginning in 1973.
45 For further information regarding Fenn’s research see his annual reports on the Chemical Stabilization of Prehistoric Structures at Chaco Canyon National Monument.
47 2013 Preservation Activities at WUPA, 8.
Section 3: Field Observations

On November 13th-14th, 2018, a site visit was made by the author to Wupatki National Monument to examine original and stabilization mortars in situ and at Wupatki’s museum collection. At Wupatki Pueblo, the location and condition of the stone and mortar masonry were assessed, and mortar sample locations were identified for park archaeologists to collect at a later date pending SHPO approval. Additionally, constituent materials (soil, sand, and water) used to formulate the current stabilization mortars were collected and sent by Park administration to the Architectural Conservation Lab (ACL) at the University of Pennsylvania.

3.1 Site Organization and Preservation

The current cyclical maintenance program as established at Wupatki begins with a condition assessment conducted by NPS archaeologists that defines the scope of work for each year. Treatment recommendations are based on existing guidelines.48 These levels of treatment are determined by the amount of retained original fabric within individual walls and are divided into four distinct approaches:

- **Approach 1.** 100% of original fabric is retained and has not been impacted by any past stabilization intervention. Continue existing original character and appearance of fabric.

- **Approach 2.** More than 50% original fabric is retained and has been minimally to moderately impacted by part stabilization repairs. Continue existing original character and appearance, remove non-characteristics stabilization materials and techniques (where feasible).

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• **Approach 3.** Less than 50% but more than 10% original fabric is retained. Continue the existing character and appearance of original fabric where possible but continue existing stabilization appearance where necessary.

• **Approach 4.** Less than 10% original fabric is retained. Continue existing stabilization appearance. Maintain the mass and form, as well as its stability and safety.

Preservation work takes place from approximately May to October and is performed by the NPS archaeologists with assistance from Arizona Conservation Corps (AZCC) crew members.\(^49\) Areas requiring treatment are designated as “High”, “Moderate,” or “Low” priority based on preservation treatments needed to maintain specific features in a good and stable condition.\(^50\) Treatment priorities are based on observed environmental and human impacts that could affect the structural integrity of the site. Each year, different priorities are identified and preservation treatments are focused on different portions of the site depending on what areas are designated as “High”. Work that stabilizes the resource or mitigates further deterioration is prioritized, acknowledging that deferring needed preservation treatments will only lead to more complex and costly work in the future. This treatment prioritization process results in extensive work, including removing previous deteriorating stabilization mortar and selectively repointing wall joints and voids on walls using new stabilization mortar. In 2016, approximately 23 gallons of stabilization mortar was removed and 92 gallons of amended mortar was added to the South Unit at the Wupatki Pueblo.\(^51\)

The current stabilization mortar at Wupatki National Monument is comprised of soil, sand, and water with various percentages of Rhoplex™ E-330 added depending on specific

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\(^{49}\) 2016 Preservation Activities at WUPA, 8.
\(^{50}\) 2016 Preservation Activities at WUPA, 6.
\(^{51}\) 2016 Preservation Activities, 42.
locations and performance requirements. Coarse commercial sand is mixed dry with the soil supply, typically one-part sand to two parts soil by volume, before adding liquid. The sand helps strengthen the mortar and control cracking. Water is potable and sourced from a well located at the park. Wupatki National Monument uses both Wupatki well-tap water and Walnut Canyon well-tap water. The crew frequently fills 6-gallon plastic containers of water at Walnut Canyon and transports them to the work site. These containers are only stored for short (2-3 day) periods of time. Unamended formulations are used for fill and are occasionally mixed as a slurry for filling large ground surface voids. For amended formulations, Rhoplex™ E-330 is mixed with water. A ratio of 4:1 water to Rhoplex (by volume) is used as a basic repointing mix. A 3:1 water to Rhoplex ratio is used for capstones, and 2:1 if needed in special circumstances that require higher strength. Less water means a higher percentage of Rhoplex and a stronger, less permeable mortar.

Imperative to preservation is the pre-stabilization documentation that accounts for lost archaeological material during the archaeological process. Documentation provides a record for future preservation efforts in evaluating the effects of past treatments. All treatment activities are extensively documented through annotated photographs, data sheets, and written narratives of the specific work completed. Photographs of all completed work consist of “Before” and “After” images with “During” photos included when necessary. This documentation process follows the requirements set forth in the *Ruins Preservation Plan and Implementation Guidelines*. This detailed documentation proved incredibly useful in identifying previous stabilization mortar campaigns throughout the North and South Pueblos.

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3.2 Conditions Survey

Prior to the site visit, a rapid assessment survey was developed by the author for assessing the different stabilization campaigns (mortars) and the original precontact masonry. By examining the mortars in situ, we were able to obtain qualitative performance data for previous and current stabilization mortar formulations. A conditions survey of the stone masonry and mortar was performed to consider the effects of each component (i.e., mortar and stone) on the other and therefore their compatibility over time.

Due to the limited timeframe (a two-day site visit), specific walls were identified by Ian Hough, NPS Chief of Cultural Resources for Flagstaff National Monuments, for a targeted assessment. These walls were selected in order to obtain a general understanding of the conditions present at the Wupatki Pueblo. To achieve a representative sampling, walls were selected from different rooms in the South and North Pueblo. Various elevations (north, south, east, west, interior, and exterior) and exposures (protected, semiprotected, unprotected) were surveyed to examine the affect environmental parameters might have on wall and mortar performance as observed in the field.53

The rapid assessment survey targeted the condition of both mortars and the associated original and repair masonry. Mortars were examined to observe their levels of durability, security, erosion, loosening, flaking, and other signs of deterioration. Assessment of the condition of surrounding masonry included examining the effects of differential weathering, cracking, basal erosion, and other modes of degradation relative to the specific surrounding mortar types. Because this survey was designed to achieve a general understanding of wall performance,

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53 A map of all surveyed walls can be found in Appendix C
observations were written as descriptions rather than assigning numerical values to the level of deterioration or providing a finite checklist of conditions.54

Overall, the Moenkopi sandstone was found to be in fair condition and did not exhibit extreme differential weathering relative to the specific mortar types, such as the soil cement mortars. Stone degradation appeared to be caused by the combination of its unique intrinsic qualities (mineralogy, porosity, and orientation) exacerbated by poor drainage and high moisture in addition to the presence of high cement stabilization mortars. Structural cracks were not commonly observed, although some were attributed to cement repair mortars of past decades. Stone erosion was common, particularly in locations where cement mortar surrounding the sandstone was exposed or at the base of walls exposed to water runoff. Due to the extreme variation between stones, it was often difficult to assess whether degradation was caused by

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54 Survey forms can be found in Appendix D.
extrinsic factors or simply the natural weathering of physically inferior stones. Fortunately most stones were laid in their natural bed avoiding structural destabilization from delamination.

Poor water drainage was the main deterioration context for the assessed mortar. Areas that have been repeatedly exposed to water in the form of rain and melting snow generally have crumbling, eroding, or missing mortar, presumably from salt and freeze-thaw cycling. This commonly results in open joints or mortar showing signs of deterioration on the lower walls and where water runoff has formed a path. Lower areas commonly displayed friable mortar, especially in locations where stones provide a shelf for water and snow to collect and feed the masonry wall. In comparison, wall sections containing recent repointing campaigns (since 2013) often are intact but may also display signs of deterioration as well. Fissures in the stabilization mortars range from micro cracks to large fragments of material cracking and detaching from the

Figure 6 The west interior wall of Room #7 showed significant deterioration, particularly on the northwest part of the wall (pictured here). This room had visible evidence of multiple mortar campaigns including cement, 1980s mortar with cinders, and 1990s large aggregate.) Deterioration of the Moenkopi sandstone can also be seen. Dickensheets, 2018.
walls. In general, it proved difficult to identify the more recent mortar campaigns from specific years. Annotated photographs from previous stabilization efforts were essential in locating more recent mortar material. They also proved crucial in identifying where material had gone missing due to the lack of physical evidence.

3.3 Sampling

Prior to visiting the site, original and stabilization mortar samples collected by the park in 2001 were examined at Wupatki’s museum collection. These samples provided a visual introduction to the variety of mortars present on site. Once on site, the different mortar campaigns were more easily identifiable, such as the cinder and Rhoplex™ E-330 clay mix of the 1980s that displays large black aggregate. During the conditions survey, specific mortar locations were identified for sampling. This was achieved by annotating photographs on a spreadsheet with the location and brief description of the mortar sample.

Currently, Wupatki Pueblo’s walls display a variety of modified or amended stabilization mortars. The collected samples provide great insights into their composition and performance. Sampling took into account three major variables including mortar type, location, and date. Mortar types included both amended and unamended, in addition to the number of amended formulations. The locations of samples were representative of both the North and South Pueblos, along with the different qualities of the rooms and walls they were taken from (i.e. those with significant exposure or from interior walls). Finally, the date when the material was introduced was considered for selecting sample locations. Twenty-one samples were identified while on site.
and were later extracted by an NPS archaeologist. \textsuperscript{55} Samples for further analysis ranged between 50-100 grams.

\textsuperscript{55} Further mortar sample information can be found in Appendix C which includes sampling locations and Appendix E which includes photomicrographs of the mortar samples.
Section 4: Characterization and Testing

This section describes the material characterization and performance testing methods employed for this research, including modifications made to the testing standards. A complete Testing Matrix including property, test method, reference, number of samples, and sample shape/size can be found in Appendix F. Data from these tests are presented in Section 5.1 and interpreted in Section 6.1. A more in depth “Testing Manual” detailing the specific equipment and procedures used can be found in Appendix G.

Laboratory protocols for this project have been divided into three categories: material analysis, performance evaluation of existing material (soil characterization), and mortar performance testing. Samples of soil currently used at Wupatki for stabilization were sent to the Architectural Conservation Laboratory at the University of Pennsylvania for preparation. Two types of soil types were received: past stabilization soil “Nissan Red” and “Moriah” soil, which is currently used. Both soils were passed through a ¼” sieve (0.250 in, 6.35mm) at Wupatki prior to shipping. Once received the soils were transferred to 5-gallon plastic buckets with the lids removed to allow the soil to dry. ASTM STP 447 B – Manual on Test Sieving Methods was referenced to ensure the bulk samples were well mixed prior to sampling.56

4.1 Soil Characterization

All tests selected for soil characterization were conducted according to standards established by the American Society for Testing and Materials (ASTM). The previous soil supply,
“Nissan Red” and the currently used “Moriah” soil (both with and without added sand) were characterized according to the following parameters:

- Color
- Particle size distribution (granulometry)
- Soil particle description

Only the Moriah soil was characterized using the following parameters:

- Atterberg limits (liquid limit, plastic limit, and plasticity index)\(^57\)
- Qualitative soluble salts
- Qualitative organic content
- Carbonates (acid-soluble) content
- pH
- Clay Mineralogy—Methyl Blue Adsorption Test and X-Ray Diffraction

### 4.1.1 Particle Size Distribution

Both Nissan Red and Moriah soils were classified by grain size, shape, and sorting which defines the soils’ microstructure. Analysis of soil particle size distribution was performed according to ASTM D6913/D6913M-17, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*.\(^58\) An ASTM sieve stack and mechanical sieve shaker were employed. Using the percentage retained on each sieve, each soil’s grain size distribution (granulometry) was identified as either coarse sand (passing No. 4 and retained on No. 10),

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\(^57\) Atterberg Limits were tested on the Moriah soil using water and then on four formulations of Rhoplex to see the impact of the acrylic polymer on the Plastic and Liquid Limits of the soil.

medium sand (passing No. 10 and retained on No. 40), fine sand (passing No. 40 and retained on No. 200 sieve) and silt and clay fines (retained in pan).

Particle size designations established by ASTM were followed using the following characterization:59

Table 1

<table>
<thead>
<tr>
<th>Particle Size Designations</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>76.2 mm – 4.75 mm</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>4.75 mm – 0.075 mm</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.075 mm – 0.02 mm</td>
</tr>
<tr>
<td>Silt</td>
<td>0.02 mm – 0.002 mm</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;0.002 mm</td>
</tr>
</tbody>
</table>

4.1.2 Combined Wet and Dry Sieving

In addition to the typical sieving method, a Combined Dry and Wet Sieving was performed following ASTM D1140, Standard Test Method for Determining the Amount of Material Finer than 75-μm (No. 200) Sieve in Soils by Washing.60 This test method uses sedimentation with a hydrometer to account for particles smaller than 75-μm (silt and clay). Because fine particles tend to agglomerate and adhere to coarser particles, which was observed during sieving, the soil was treated with 4% sodium hexametaphosphate (HMP) (40g/L) before sieving.

The sedimentation test is theoretically based on Stokes’ Law, which states that the square diameter of an approximately spherical particle is proportional to that particle’s terminal velocity. Although clay particles are not spherical, Stokes’ Law can be applied by approximating the various sizes of the particles in the clay fraction of a soil. Therefore, the sedimentation test can provide a fairly accurate method to determine the percent clay-sized particles in the soil. 61

4.1.3 Soil Particle Description

Color was measured in accordance with ASTM D1535-97, *Standard Practice for Specifying Color by the Munsell System*. 62 Soils and sieved fractions were viewed under north-facing, indirect daylight illumination and compared to the standard Munsell soil-color reference set. Soil samples were viewed with a Nikon SMZ1 stereoscopic microscope and described on the basis of particle size, sphericity, roundness, and sorting. The presence or absence of visible organic content was also noted.

4.1.4 Plastic Limit, Liquid Limit, and Plasticity Index

The Plastic and Liquid Limits are used to classify and characterize soils based on water content. High water content causes the soil to behave more like a liquid. As water content decreases, the soil becomes more plastic. The liquid and plastic limits of the soil were determined according to ASTM D4318-17, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. 63

The Plastic Limit of a soil indicates the boundary between the plastic and semi-solid states of the soil. This limit is determined as the lowest water content at which the soil can be

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rolled into 3mm threads without the threads breaking into pieces. The Liquid Limit of the soil will indicate the point at which the soil, when mixed with water, has physical qualities closer to those of a liquid than a solid. This limit is determined by the water content at which two halves of the soil cake placed in a Casagrande device flow together for a certain distance after being separated and having the cup dropped a specific number of times.

The Plasticity Index indicates the strength capabilities of the soil and is calculated by subtracting the soil’s Plastic Limit from its Liquid limit. The Plasticity Index is largely reliant on the amount of clay in a soil. A high Plasticity Index indicates an excess of clays in the soil which have the potential to become too expansive. Alternatively, soils with a low Plasticity Index require a minimal amount of water to shift from a solid to liquid state. The strength of a soil often increases when its Plasticity Index is higher. For this test, the four different Rhoplex amended mortar formulations were tested to observe the impact of Rhoplex on the soil’s Plastic and Liquid Limits.

4.1.5 Qualitative Soluble Salt Analysis

Merck indicator strips were used to detect the presence of soluble salts such as chlorides (Cl⁻), nitrates (NO₃⁻) and sulfates (SO₄²⁻). Soils were soaked for one hour after which test strips were immersed in the solution and observed for color changes on the strip indicators. Specific color changes correlate to a range of ions present, but do not provide a full quantitative analysis. The presence of soluble salts in the soil could damage the mortars and masonry through efflorescence.
4.1.6 Quantitative Organic Content Analysis

This test was performed according to ASTM C40/C40-16, Standard Test Method for Organic Impurities in Fine Aggregates for Concrete using the Standard Color Solution Procedure. This test is designed to examine the fine aggregates to be used in concrete for the presence of organic material in amounts that would affect the performance of the concrete. Because soils tend to contain organic content, the results of this test serve more as indicators of certain performance characteristics exhibited by the mortars containing these soils.

4.1.7 Carbonate (Acid-Soluble) Content

The carbonate content of the soil was tested using acid digestion (15% hydrochloric acid solution) after a spot test resulted in effervescence. This test is an adaptation of a standard gravimetric mortar analysis procedure to quantify the amount of carbonate content in a soil. The soil sample was dried to a constant mass, weighed, and then submerged in 15% HCl. This mixture was then agitated, diluted with deionized water, and filtered. The collected fines were dried and weighed along for the reduction in mass due to the dissolution of carbonate material and emission of CO₂ to be calculated.

The presence of carbonates in a soil indicates how the soil will perform when used in mortar and in its particular environment. Because the presence of natural carbonates is common among southwestern soils, this is a common test that will indicate performance characteristics of the mortars.

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4.1.8 pH

High and low levels of pH in a soil can affect the stability of clay minerals. Soil pH was measured according to ASTM D4972-18, *Standard Test Methods for pH of Soils.*\(^6\) The basis for this test was “Method B” which measures pH using pH sensitive paper. This method provides an approximate estimate of the pH depending on the acidity and alkalinity of the soil.

4.1.9 Methyl Blue Adsorption Test

This test was performed according to ASTM C1777-15, *Standard Test Method for Rapid Determination of the Methylene Blue Value for Fine Aggregate or Mineral Filler Using a Colorimeter.*\(^6\) The test quantifies the ionic absorption capacity of a material by measuring the amount of methylene blue required to cover both the external and internal surface of the clay particles within the soil sample. Ultimately, the methylene blue identifies the presence of swelling clays that would be highly unstable in these mortars.

4.1.10 X-Ray Diffraction

X-Ray Diffraction (XRD) was performed to assist in determining the mineralogy of the clays in the Moriah soil. XRD is a technique used for determining the atomic and molecular structure of crystals. Only material comprised of crystalline structures (i.e. inorganic) can be analyzed using XRD. The analysis is performed by comparing different peak positions and intensity value with reference patterns. Because clay minerals are crystalline in nature, XRD is well suited for soil–clay analysis. Other methods of analysis include scanning electron microscopy (SEM) and thermal analysis. Testing was performed at the University of Pennsylvania’s Laboratory

for the Research of Structural Matter using a Rigaku MiniFlex™ benchtop powder X-ray
diffraction instrument designed to provide qualitative and quantitate phase analysis of poly-
crystalline materials.

4.2 Mortar Performance Testing

This section describes both the preparation of amended earthen mortar samples and the
tests performed. While this section identifies modifications made to any testing standards, a
more in depth “Testing Manual” detailing the specific equipment and procedures used can be
found in Appendix G.

Four aqueous concentrations of Rhoplex™ E-330 were chosen for the mortar
formulations. Two concentrations represent the current field applications of amended mortars at
the Wupatki Pueblo. A control containing no Rhoplex and a fourth formulation using a lower
amount of Rhoplex were also selected for mortar testing.

Table 2 Rhoplex™ E-330 formulations.

<table>
<thead>
<tr>
<th>Percent E-330™ (47% solids) in Water for Mortar Mix</th>
<th>Approximate Equivalent Ratio E-330: H₂O (parts by volume)</th>
<th>Percent Solids E-330 for each Ratio (47% solids x %Rhoplex in H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0:1 (Control)</td>
<td>0%</td>
</tr>
<tr>
<td>12.5%</td>
<td>1:7</td>
<td>5.875%</td>
</tr>
<tr>
<td>20%</td>
<td>1:4</td>
<td>9.40%</td>
</tr>
<tr>
<td>25%</td>
<td>1:3</td>
<td>11.75%</td>
</tr>
</tbody>
</table>

All soil sieving was done according to ASTM D422 and the STP 447 B Manual on Test
Sieving Methods. The mortars were prepared at the Architectural Conservation Laboratory at the
University of Pennsylvania. The soils obtained from Wupatki National Monument were mixed
according to ASTM C305-14, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of a Plastic Consistency*.\(^67\) This ASTM was modified to accommodate the soil material. The soil was sieved through a No. 8 sieve to ensure homogeneity of the material and to remove large clumps, pebbles, and other extraneous material that would lead to an inconsistent final product. Although Wupatki limits their sieving to a \(\frac{1}{4}''\) sieve, this extra sieving step was found necessary to control as many variables as possible in laboratory testing conditions.

This ASTM test was modified to standardize a mixing procedure conducive for earthen mortars. This procedure was developed and used for all mortar formulations. Mortars were mixed using a Hobart C-100, 3-speed mechanical mixer. Although this research attempts to standardize the mixing of mortars, standard procedure varies greatly in the field. Varying preference for park personnel results in varying mortar consistency which can impact different characteristics in the final product. By preparing the mortar sample in a laboratory setting, there was greater control over the final mortar test samples thus ensuring uniformity within testing cohorts.

4.2.1 Consistency (Slump Test)

The appropriate water content for each mortar mixture was determined and described as consistency. Optimal working properties require that mortar be wet enough to have a thoroughly plastic consistency. At the same time, overly wet mortars result in increased shrinkage as the excess water eventually evaporates from the mixture. The common practice of determining a mortar’s optimal consistency relates to its ability of stick to the inverted surface of a trowel. This guided the initial testing phases of creating formulations with the test providing a

more quantitative indicator of the mortar’s consistency. Test batches of the formulations were mechanically mixed with the Rhoplex deionized water added incrementally until the mortars were judged to have the optimum consistency. This ratio was then used for all other mortar formulations. An approximate ratio of 1:7 parts (by volume) liquid to solids was found to provide optimal consistency. However, specific volumes varied from batch to batch. The basis for this test is ASTM C1437 Standard Test Method for Flow of Hydraulic Cement Mortar with reference to ASTM C230/C230M-14 Standard Specification for Use in Tests of Hydraulic Cement.

4.2.2 Linear Drying Shrinkage Test

The basis for this test is ASTM C1148, Standard Test for Measuring the Drying Shrinkage of Masonry Mortar.68 Additional reference is made to ASTM C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete.69 The molds for this test were custom made using a plywood base lined with luan veneer on both sides and were coated with mineral oil. Each mold is designed to make four prism samples of approximately 1”x1”x6-¼” dimension.70 This ASTM test requires that specimens be removed from their molds 72 hours after being formed. Because this standard is for masonry mortar, it was modified for the earthen mortar samples which have a significantly faster set and dry rate. Samples were measured twice, immediately after being placed into their molds and then after they had completely dried under controlled conditions. Five samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twenty samples.

70 The molds had been previously prepared by Nityaa Iyer in 2014.
4.2.3 Qualitative Visual Shrinkage

Dimensional stability of the earthen mortar was assessed through qualitative volumetric shrinkage. This test method involves placing the mortar formulations into terra cotta saucers.\textsuperscript{71} Shrinkage and cracking can then be visually assessed after the mortars have fully dried. Although this test does not result in quantitative measurements, it provides insight into how the mortars will shrink in controlled conditions. Three samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twelve samples.

4.2.4 Wet/Dry Resistance

This test determines the resistance of earthen mortars to repeated wetting and drying. The basis for this test is D559/D559M – 15, \textit{Standard Test Method for Wetting and Drying of Compacted Soil-Cement Mixtures}.\textsuperscript{72} Because these earthen mortar samples are more fragile than the soil-cement mixtures, the test was modified to exclude physical abrasion. The earthen mortars would not have been able to withstand this level of abrasion. Cylinders of soil were soaked in room temperature deionized water for five hours, and then oven-dried overnight at approximately 90° C. Samples were weighed after each drying cycle to determine the mass of material lost per cycle. Five samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twenty samples.

4.2.5 Freeze/Thaw Resistance

This test qualitatively assesses the resistance of earthen mortars to repeated freezing and thawing. The basis for this test is ASTM D560/D560-16, \textit{Standard Test Methods for Freezing

\textsuperscript{71} Iyer, 2014 and Washa (1966, 190).
and Thawing Compacted Soil-Cement Mixtures. This test specifically addresses the destructive properties of freeze/thaw by constantly keeping the samples in a moist environment. By keeping the samples moist, only freeze/thaw damage is observed. While this might differ from environmental conditions seen in the field (earthen mortars are frequently not wet when forced through a freeze/thaw cycle), it eliminates the added variable of having the sample dry out and complicate cause/effect explanations.

Similar to the test method for Wetting and Drying, this test was modified to exclude physical abrasion. Cylinders of soil were placed on an absorbent felt pad soaked in water and were then cycled through freezing (at approximately -5 to -10° C) and thawing (ambient laboratory temperature, around 20° C), always remaining moist. Changes in the condition of the earthen mortars were noted at the end of each thawing cycle. Samples were turned over on end following the thaw cycle until this step proved too physically damaging to the samples. Five samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twenty samples.

4.2.6 Water Vapor Permeability

Water vapor permeability is a critical indicator of a mortar’s compatibility with the masonry system. Considering that water will inevitably enter the wall system it is imperative that the mortar does not impede the egress of that water in vapor form. The vapor permeability of each mortar type indicates how Rhoplex affects water vapor permeance. The basis for this test is ASTM E96/E96M – 16, Standard Test Method for Water Vapor Transmission of Materials. This

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test is designed to determine the effect of varying quantities of Rhoplex™ E-330 on water vapor transmission. The water transmission rate described the average rate at which water moves through the material. In the “Water Method” selected for this test, the sample is sealed in the open mouth of a plastic container containing deionized water and placed in a test chamber. The sample test assemblies were weighed regularly and kept in monitored chambers where the desiccant was regularly changed to maintain a low relative humidity. Five samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twenty samples.

4.2.7 Modulus of Rupture

Also known as the three-point bend test, this test measures the amount of force required to break earthen mortar prisms thus indicating the sample’s flexural strength. This test follows ASTM D1635/D1635M – 12, Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading. Testing took place at the Mechanical Testing Center of the Laboratory for Research on the Structure of Matter at the University of Pennsylvania using an Instron Universal Testing Machine, model 4206. This test calls for prism shaped mortars to be placed on two blunt knife edges while a force is applied from above. The distance of the knife supports remained at a constant 2 inches apart throughout testing. This machine records both the total load (lbs.) and displacement (in) required to break the prism. Five samples of each earthen mortar/Rhoplex™ E-330 formulation were tested for a total of twenty samples.

4.2.8 Bond Strength and Adhesion Test

One of the challenges faced at Wupatki Pueblo is the adhesion of stabilization mortars to the original sandstone masonry and previous Portland cement bedding mortar campaigns.

Although the Portland cement mortars remain intact, they negatively impact the surrounding original masonry and prove near impossible to remove in their entirety without damaging the stone. As a result, current earthen mortar formulations are required to form a bond to these cement mortars. This test sought to quantifiably measure the bond/adhesion strength of the amended mortar formulations. The basis for this test is ASTM D2095-96, *Standard Test Method for Tensile Strength of Adhesives by Means of Bar and Rod Specimens.* For this situation, the testing was modified to accommodate the specified substrates and the mortar material.

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Section 5: Data

A Q-Test was used to identify and discard outliers in the test results. This test can only be used once per set of test results and can only identify one outlier. The formula for the q-test is as follows:

\[ Q = \frac{\text{gap}}{\text{range}} \]

\( \text{Gap} = \) the difference between the suspected outlier and the nearest value to the outlier

\( \text{Range} = \) the difference between the highest and lowest values

Using a 95% confidence level and the total number of samples, a q-table (Qtab) was referenced. If \( Q > Q_{\text{tab}} \), the suspected outlier was discarded. For the purposes of this report, only the critical values for a 95% confidence level were referenced.

Table 3 Q-Table

<table>
<thead>
<tr>
<th>Number of value (N)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{\text{crit}} )</td>
<td>0.970</td>
<td>0.829</td>
<td>0.710</td>
<td>0.625</td>
<td>0.568</td>
<td>0.562</td>
<td>0.493</td>
<td>0.466</td>
</tr>
</tbody>
</table>
5.1 Soil Characterization

Soil characterization data can be found in Appendix H.

5.1.1 Particle Size Distribution

Graph 1 Particle Size Distribution of the soils used at Wupatki National Monument for stabilization mortars.

Graph 2 Particle Gradation of the soils used at Wupatki National Monument for stabilization mortars.
The particle size distribution of Wupatki soils was plotted on a semi-logarithmic graph and grouped into coarse, medium and fine sand, and fines (silts and clay). The results indicate that the Moriah and Nissan Red soils are both well graded with a similar grain size range. The addition of sand to the Moriah soil resulted in a higher percentage of coarse and fine sand, but a decrease in medium sand.

5.1.2 Combined Wet and Dry Sieving

Graph 3 Hydrometer Readings throughout the testing period.
The high hydrometer readings for the Moriah soil indicate a significant amount of fines. The amount of fines was so large that the hydrometer readings were greater than 60 for the first 30 minutes of testing (Graph 3). Additionally, microphotographs were taken of the Moriah soil after the sedimentation test. These images demonstrate the color of the soil without the clay. Detailed calculations of the sedimentation test have been included in Appendix H.

### 5.1.3 Soil Particle Description

The Moriah soil is reddish brown (5YR 5/4 and 5 YR 5/3) in color the Nissan Red soil was also a reddish brown (2.5YR 5/4.) The addition of the commercial sand resulted in the Moriah soil mix as having a slightly more yellow color. Moriah soil sands (intrinsic) were generally sub-rounded with a combination of both equant and elongate shaped particles. Occasional organics such as wood and other vegetal material were retained on sieves 16, 30, and 50.

### 5.1.4 Plastic Limit, Liquid Limit, and Plasticity Index

All of the formulations were considered plastic as they could be rolled down to the 3mm. Plastic Limits were calculates using the following formula:
\[
PL = \frac{\text{mass of water}}{\text{mass of oven-dry soil}} \times 100\%
\]

These values are recorded to the nearest whole number on the data sheet.

The soils displayed Plastic Limits between 19 and 21. The unamended soil displayed an average Plastic Limit ranging between 20-21. The samples containing Rhoplex tended to have slightly lower Plastic Limit ranging from 18 to 20. Between the amended formulations, there was no clear indication that higher amounts of Rhoplex resulted in a lower Plastic Limit. This difference suggests that the soils mixed with Rhoplex required more water to reach their optimal Plastic Limits.

To determine the liquid limits, the moisture content of the soils are plotted against the corresponding number of drops in a Casagrande device as a logarithmic scale (Graph 5). The “flow curve” is the best straight line that can be drawn through the plotted points. The liquid limit is read as the moisture content corresponding to the intersection of the flow curve with the 25-drop ordinate, rounded to the nearest whole number.

Graph 5 Results from the Liquid Limit Test.

Liquid limits for the soil samples ranged from 27 to 40. The unamended soil sample had the lowest liquid limit at 27 while the amended soil samples all displayed higher liquid limits.
Among the amended soils, there did not appear to be a relationship between the amount of Rhoplex in the formulation and the liquid limits. It should be noted that the plotted ordinates for the 1:3 and 1:4 Rhoplex formulations did not result in a linear relationship as was the case with the 1:0 and 1:7. As a result, the “flow curve” does not adequately represent the variety of values found for these formulations. Calculations for the Plasticity Index were still calculated. The difference between the liquid limit and the Plastic Limit is calculated to give the Plasticity Index of the soil:

\[
\text{Plasticity Index} = \text{Liquid Limit} - \text{Plastic Limit}
\]

Plasticity Index is reported to the nearest whole number.

<table>
<thead>
<tr>
<th>Formulation</th>
<th>Liquid Limit</th>
<th>Plastic Limit</th>
<th>Plasticity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:0</td>
<td>27</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>1:7</td>
<td>30</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>1:4</td>
<td>40</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>1:3</td>
<td>33</td>
<td>19</td>
<td>15</td>
</tr>
</tbody>
</table>

Silty soils have a Plasticity Index lower than 4 while clayey sands have relatively higher indices of plasticity. The Plasticity Index for all formulations ranged from 7 to 21 when rounded to a whole number indicating that all of the soil formulations performed as clayey soils.

### 5.1.5 Qualitative Soluble Salts Analysis

Qualitative test strips for chlorides (Cl-), nitrates (NO₃-) and sulfates (SO₄²-) were used to test for the presence of soluble salts in both Nissan Red and Moriah soils. Both soils tested negative for all these salts.

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5.1.6 Organic Content Analysis

The organic content test resulted in no color change when the soil sample was allowed to stand in the sodium hydroxide solution for over 24 hours. Because transmitted light could not pass through the soil sample, it could not be compared to the standard color solution. This indicates the absence of organic material from the Moriah sample.

5.1.7 Carbonate (Acid-Soluble) Content

Observed effervescence indicated the presence of carbonates in the Moriah soil. Standard gravimetric analysis indicated that the soil had 4.96% acid-soluble material.

5.1.8 pH

The pH of the Moriah soil was determined to be approximately 6.5 making it slightly acidic. As a concrete amendment, Rhoplex is manufactured to exist in a highly alkaline environment. However, because the soil is only slightly acidic its pH level most likely will not interfere with the film formation of the emulsion.

5.1.9 Methyl Blue Absorption Test

Addition of 125 mL of 10g/L methylene blue trihydrate to the liquid soil solution did not produce a blue halo, thus determining that there were no swelling clays present in the soil sample.

5.1.10 X-Ray Diffraction

X-Ray diffraction definitively detected the presence of quartz and dolomite in the Moriah soil sample. Clay minerals are incredibly small (less than 2µm) and exhibit affinity for water with resulting plasticity not exhibited by other materials, even those of clay particle size and smaller.  

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Of the potential clays identified in XRD, only Kaolinite was definitive in its identification and is considered to be one of the least active clays. Other potential crystalline structures include Hematite and Calcite. Overall, the XRD confirmed previous tests (such as the Methyl Blue Absorption Test and carbonate content).

5.2 Mortar Performance Testing

Mortar performance data can be found in Appendix I.

5.2.1 Consistency (Slump Test)

The consistency or flow of a mortar is expressed as an increase in average base diameter of the mortar mass, expressed as a percentage of the original base diameter (100 mm, 3.94 in). Flow is calculated by dividing “A” by the original inside base diameter in millimeters and multiplying by 100 where:

\[ A = \text{average of four readings in millimeters, minus the original inside the base diameter in millimeters.} \]

Overall, it was found that Rhoplex reduced mortar flow when compared to the unamended soil mortar. Therefore, to increase mortar workability, slightly more liquid (Rhoplex and water) had to be added to the mortar formulations to provide optimal consistency. This slight increase in liquid did not significantly affect the percent solids of Rhoplex in the formulations. Factors such as relative humidity in the laboratory may have contributed to the variability in the amount of liquid necessary for the mortars to reach optimum flow.

5.2.2 Linear Drying Shrinkage Test

Because this test was modified given the fragility of earthen mortars, the formula does not include the effective gauge length. Instead, the percent shrinkage is calculated by dividing the difference in initial and dry lengths by the initial length to calculate the percent shrinkage.
To calculate percent shrinkage (S) of the five specimens, the following formula was used:

\[ S = \frac{(L_1 - L)}{L_1} \times 100 \]

where:

\[ L_1 = \text{initial measurement (in)} \]
\[ L = \text{measurement after drying (in)} \]

No outliers were determined using the Q-Test. Samples exhibited an average shrinkage of approximately 4.6%. The unamended samples had an average shrinkage that was slightly below average at 4.2%. Among the amended samples, the overall shrinkage was higher than average at 4.75%. However, the average shrinkage of samples made with the lowest concentration of Rhoplex was lower than the unamended. The earthen mortars made with the highest concentration of Rhoplex did display a greater percentage of shrinkage than the other samples at 5.76%. This cohort also displayed the smallest standard deviation indicating that all of the
samples had similar shrinkage levels. Standard deviation for the other cohorts ranged from 0.37% to 0.45%.

5.2.3 Qualitative Visual Shrinkage

Upon fully drying, all earthen mortars placed into glazed terra cotta saucers all displayed cracking-signs of shrinkage. Cracks typically formed on the perimeter of the mortar coupon and extended towards the center of the sample.

5.2.4 Durability: Wet/Dry Resistance

The wet/dry durability test concluded after 12 cycles, as prescribed by ASTM D559. This test provided both qualitative visual observations and quantitative weight loss data. This test does not directly simulate conditions seen in the field. At Wupatki, mortars are susceptible to more gradual cycles of wetting and drying which may or may not include freezing and thawing. Earthen mortars are rarely if ever submerged under water for five hours and then dried in intense heat. This testing process accelerates the weathering process in a controlled and consistent manner that allows for comparative performance analysis of different mortar formulations.
The largest loss of mass occurred after the first cycle for all sample sets, and especially the unamended samples which completely disintegrated. The amended samples lost approximately 6g of material in this initial cycle. In the subsequent cycles, amended mortars lost on average between .05 and .12g of material with no visible relationship to the concentration of Rhoplex in each formulation. Upon the final drying cycle, there was not a difference in mass lost among the three amended mortar formulations which all retained approximately 91% of their original mass. No outliers were determined using the Q-Test. Standard deviation was moderate at an average of 3.1% for all amended cohorts.

Visual observations provided insight into how the soil mortar deteriorates when subjected to intense wetting and drying cycles. Surface flaking of the amended samples was a common failure mode accompanied by fine cracks followed by material loss from the detachment of these flakes. Granular disintegration was observed only in the unamended sample set. By the final cycle, crisp edges for all three amended formulations remained intact for some samples.
while others had edges that had completely deteriorated. There was no noticeable color
difference among the different formulations after testing was completed.

5.2.5 Durability: Freeze/Thaw Resistance

The freeze/thaw durability test concluded after 12 cycles, as prescribed by ASTM D560-
16. This test only provided qualitative visual observations of freeze/thaw behavior of the soil
mortars. Because the samples never dried (as in the Wet/Dry Resistance Test) and were soft and
fragile when wet, weight loss could not be calculated. ASTM D560-16 called for the mortars to be
turned on end after each cycle. This process proved damaging to all the mortars and this step was
eliminated after the fifth freeze/thaw cycle.

All of the mortar samples changed shape immediately following the first cycle, but the
addition of Rhoplex lessened the deformation. Overall deformations included the slumping of the
samples and particle loss that was collected on the absorbent pad during the thaw cycles. Mortar
samples containing higher Rhoplex concentrations tended to have less slump and loss of material
than the unamended mortar. Any difference among the amended formulations was not
significant.

5.2.6 Water Vapor Transmission

All earthen mortar samples had a surface area of 0.5 cm² and a thickness of 1.9 cm. The
average temperature in the desiccator chamber was 20°C at which the saturation vapor pressure
was determined to be 17.54 mm Hg (2339 Pa)⁷⁹. The relative humidity within the vapor
transmission assemblies was 100%, and the average relative humidity in the desiccation chamber
was 35%.

Testing began after a brief initial period when the samples gained weight. Over a 20-day test period for water vapor transmission, all test samples were weighed daily. Data collected during the test period including individual and daily formulation averages are tabulated in Appendix I along with average water vapor transmission curves.

Water vapor transmission, WVT, was calculated in metric units as follows:

\[
WVT = G/tA = (G/t)/A
\]

where:

\(G\) = weight change (from straight line), g
\(t\) = time (hours)
\(G/t\) = slope of the straight line, g/h
\(A\) = test area (m²)

and

\(WVT\) = water vapor transmission, g/h·m².

Permeance was calculated in metric units as follows:

\[
\text{Permeance} = \frac{WVT}{S(R_1 - R_2)}
\]

where:

\(S\) = saturation vapor pressure at test temperature, Pa (1 mm Hg = 133.3 Pa)
\(R_1\) = relative humidity at the source expressed as a fraction (in the dish for water method), and
\(R_2\) = relative humidity at vapor sink expressed as a fraction (in the chamber for water method).

Average Permeability (metric perm·cm) was calculated as follows:

\[
\text{Average Permeability} = \text{Permeance} \cdot \text{thickness}.
\]
No outliers were determined for any of the sample cohorts. Samples lost an average of 0.3 to 0.5 grams of water per day. On average, total weight loss was highest among the unamended samples at 2.96%. Among the amended samples, there was an inverse relationship between the amount of Rhoplex and the percentage of weight lost. The unamended soil mortar had the highest average water vapor transmission rate at 3.5. Among the amended samples, those with a higher concentration of Rhoplex displayed lower water vapor transmission rates. This is consistent with the effect of Rhoplex on other mortar types such as those composed of lime and cement. Average permeability was highest for the unamended samples. Among the amended, permeability decreased as the concentration of Rhoplex increased but only in small magnitudes.

5.2.7 Modulus of Rupture

Mechanical testing was conducted at the Laboratory for the Research of Structural Matter at the University of Pennsylvania. All earthen mortar samples were seated atop two blunt-
edged-bearing knives (mounted on an Instron 4206 testing machine) with a 2-inch span between them. The modulus of rupture was calculated for each sample in relation to the maximum recorded load as follows:

\[ R = \frac{PL}{bd^2} \]

where:

- \( R \) = modulus of rupture, psi (lb/in²),
- \( P \) = maximum load applied at the time of breaking, lbf,
- \( L \) = span length (between supports), in
- \( b \) = width of sample tested, in.
- and
- \( d \) = depth of sample tested, in.

Data for this test includes the calculations of the modulus of rupture for each sample tested, as well as the average modulus of rupture for each formulation.

Graph 9 Results from the Modulus of Rupture Test showing the force required to rupture the samples. An exclusive mean was used to calculate quartiles. Mean is indicated with an X.
No outliers were determined for this test. Sample (1:4 C) had to be discarded because the machine was not properly reset before testing took place. Increasing the amount of Rhoplex increased the load required to break the earthen mortars. The unamended mortar samples displayed a modulus of rupture significantly less than that of the amended samples. Among the amended mortars, increased strength corresponded with the amount of Rhoplex, but there was not as great a difference between cohort sets.

In addition to the force required to break the prisms, the Instron 4206 testing machine recorded the displacement for each sample. This information indicates how brittle, or ductile, a material is. Overall, all the mortars were relatively brittle with little to no plastic deformation occurring before failure. This physical characteristic is also seen in the resulting broken samples. When the broken halves are matched up, they fit exactly into place indicating that no plastic deformation has occurred. Overall, the unamended mortars exhibited less displacement while the amended samples all displayed greater displacement. Between the amended, the formulation with the highest level of Rhoplex withstood the greatest amount of displacement. However, the other two earthen mortars displayed similar levels of brittleness.

5.3 Additional Testing

In addition to characterizing the soil and conducting mortar testing, the water supply at Wupatki National Monument was tested for pH and soluble salts. Water samples from Wupatki and Walnut Canyon were tested using pH and semi quantitative salt test strips. Typically only Walnut Canyon well-tap water is used for stabilization mortars but Wupatki well-tap water was also tested. Both water samples had pH levels of approximately 7.5 or slightly basic. The Wupatki sample did not test
positive for nitrates or sulfates; however, chlorides were identified. The Walnut Canyon sample tested negative for chlorides and sulfates, but it did contain low levels of nitrates.
Section 6: Discussion and Conclusions

6.1 Optimal Properties of Earthen Mortars

Current stabilization at Wupatki National Monument is based on the assumption that Rhoplex amended earthen mortars are physically compatible with the existing masonry ruins. This means the amended mortars display good durability while providing a good visual match with the original mortars and cause no damage to the existing stone masonry. The current assessment and evaluation program has tested these assumptions by identifying several critical properties that can be used to characterize mortar performance and considering the results in light of the current context. While the stone masonry units themselves continue to deteriorate through normal weathering, their mortar components are periodically-sometimes annually-renewed. This relationship, common for any mortared masonry system, must be considered, especially as other assumed stable contexts such as climate change.

Ideally, an optimal amended stabilization mortar should exhibit the following characteristics:

- Uniform color similar to that of the original weathered/exposed mortar
- Low shrinkage during installation and after wetting and drying
- Good consistency during installation
- Good cohesive strength
- Lower adhesive or bond strength than the cohesive strength of the Moenkopi sandstone (wet)
- Low liquid water permeability
- High water vapor permeability
• Good adhesion to the masonry and previous stabilization mortars

6.2 Soil Characterization

For this study, it was necessary to characterize the soil used to formulate the earthen mortars using standard geotechnical tests. Soil is a complex material that greatly defines the overall performance of the masonry system. All of the standard soil characterization tests (mineralogy, particle size and distribution, chemical content, organic content, etc.) can be used to assess how Rhoplex™ E-330 changes unamended soil mortar performance including weathering.

Particle size and particle size distribution have a direct effect on plastic properties such as consistency and shrinkage as well as ultimate porosity, permeability, and water vapor transmission. In well-graded aggregates, the smaller particles occupy the spaces between the larger ones creating a lower void ratio than in a poorly-graded aggregate. Poorly graded aggregates contain particles that are of similar size creating a higher void ratio than well-graded ones, and produce materials with higher porosity. Ultimately, it is these voids and how they are connected that determines a material’s porosity, permeability, and water vapor transmission.

Particle sizes and their proportions determine critical properties of a soil which affect how it will behave as a building material. Finer components such as silt and clay, become plastic when wet and can function as a binder for coarser grains. Too little fines and the building material will not bind together properly. While the addition of the commercial sand does not significantly expand the grain size distribution of the soil, it does result in decreasing the percentage of fines which have the potential to swell when hydrated and result in shrinkage upon drying.

Particle size also directly affects the plastic and Liquid Limits of a sample. Typically, a decrease in particle size requires less water to achieve plasticity. Smaller particle sizes result in
lower Plastic Limits, higher Liquid Limits, and a higher Plasticity Index. This study focused on the impacts of Rhoplex on the current Moriah soil and sand mortar formulations at Wupatki. Overall, the testing program revealed that the addition of Rhoplex™ E-330 resulted in soils with lower Plastic Limits, greater Liquid Limits, and a higher Plasticity Index. The observed differences between Rhoplex ratios were inconclusive.

Fines analysis revealed the Moriah soil contains kaolinite and calcite, both lending good stability to the soil mortar formulations.

6.3 Mortar Performance Testing

Mortar performance testing revealed the effects of different concentrations of Rhoplex™ E-330. Predictable effects of the amendment include an increase in strength and a decrease in permeability. Low concentrations of Rhoplex did not appear to have an effect on shrinkage. However, higher concentrations of the amendment resulted in greater shrinkage. Compared with the unamended soil, the addition of Rhoplex™ E-330 at all concentrations resulted in an increase in durability wet/dry and freeze/thaw cycling. While none of the unamended earthen mortars endured the initial five-hour submersion in water, all of the Rhoplex amended samples remained intact after twelve cycles. Similarly, while the unamended freeze/thaw samples experienced significant deformation, the amended samples were more likely to retain their initial shapes.
Section 7: Recommendations

7.1 Site Specific Recommendations

Rhoplex™ E-330 can only perform as well as the soil selected for mortar formulation. Previous research suggests a sandy soil (at least 60-65% coarse sand, with 10-15% clay) performs best with Rhoplex™ E-330. Additionally, soil with minimal shrinkage (i.e. not containing swelling clays) should be chosen. The Moriah soil does not contain any salts or expansive clays that should prohibit it from use. Because Moriah soil does not naturally contain enough sand to meet this grain distribution requirement, it is necessary that coarse grained sand be added.

Soil characterization is not the only measure of success for evaluating the effectiveness of Rhoplex™ E-330. Variables not found in a laboratory setting including weather, climate, masonry conditions, and varying stabilization techniques among park personnel, all of which have an impact on amended mortar performance. Much of the mortar deterioration at Wupatki Pueblo can be attributed to exposure to water. Preservation efforts already include mitigating the flow of water through the site through drainage systems that include ground water disposal systems and “evaporation ponds” — areas built on the ground level of rooms to catch runoff and impede the amount water entering drains. This preventative maintenance is critical as it redirects water from the walls and their earthen mortars. Although the deterioration of earthen mortar remains inevitable (and expected due to its sacrificial nature) efforts to identify the most durable earthen mortar that weathers in an acceptable manner is the goal of site preservation management.

81 Hartzler, 97.
7.2 Further Research

Although the tests performed provide standardized methods for evaluating new mortars, they do not replicate field conditions. Depending on their location, mortars in different walls are subjected to different environmental conditions, as seen in the field condition assessment as well as different functions such as wall caps. While some earthen mortars experience significant exposure to water, such as the top and base of walls, others remain dry for most of the year but endure intense mechanical abrasion from wind.

The following topics are recommended for further research specifically at Wupatki National Monument, but can be applied to other sites with earthen architectural components:

- Complete site survey of mortars with a focus on those using the Moriah soil supply

A complete site survey will allow for an evaluation of the mortars in real time and in different contexts. Because nearly all of the stabilization mortars observed in the rapid condition survey were formulated using the Nissan Red soil, a survey of 2018 mortars is necessary to obtain real time evidence of performance data of the current formulation. By broadening the survey to the entire site, trends in mortar and masonry deterioration can be better understood.

- Research on the masonry wall systems and a survey of risk and threat across the entire site

Current earthen stabilization mortars are only one of several components of Wupatki Pueblo’s masonry walls. It is necessary to understand the wall as a system, including the impacts of previous stabilization mortars that remain intact as well as the nature and extent of the original construction (wall core and wall junctures).
• Further research into the physical and mechanical characteristics of the Moenkopi sandstone

The Moenkopi sandstone displays extreme variability requiring multiple samples for testing. Although it is assumed that the stone displays greater strength and lower permeability than the earthen mortars, mechanical and porosity testing will confirm the compatibility of the stabilization mortars. Additional analysis such as petrography would provide further insight into their composition and performance.

• Develop a test for determining the bond/adhesion strength of stabilization mortars to the Moenkopi sandstone and the Portland cement repair mortars

A standardized bond/adhesion test should be developed and carried out for the stabilization mortars to determine the bond strength of Rhoplex™ E-330 with stone and existing Portland cement bedding and pointing mortars. The inability to easily remove earlier Portland cement mortars and the desire to conceal their presence means earthen mortars need to bond reasonably well not only to the stone, but to these unsightly mortars. Poor bond and loss of repair mortar is a continuing problem at many sites.

• SEM photomicrographs to further illustrate the interaction of the Rhoplex™ E-330 with the Moriah soil

Scanning Electron Microscopy can reveal surface characteristics and micromorphology of the amended earthen mortars. SEM is recommended for both laboratory and field specimens to reveal differences between the samples. With SEM photomicrographs, the strands of the
polymer can be seen either cohering particles fresh samples or fragmenting in samples deteriorated by laboratory tests or field conditions.  

- Field trials in the form of test walls to assess mortar performance in the field

The design and construction of test walls will allow the controlled measurement of wall performance and mortar deterioration over real time in the field. The design and location of these walls must be carefully considered (i.e. not built so close together that one shields the other from the elements). Internal monitoring methods for moisture and temperature should be included to better understand wall performance and the effects of different mortars on them.

7.3 Summary

The National Park Service is responsible for managing many of the most significant Ancestral Puebloan precontact sites in the Southwestern United States. As a land of dramatic geological and climate variability, stabilized sites in this area require specified recommendations for preservation materials that will perform effectively and compatibly with their microclimate and historic construction systems. Although Wupatki Pueblo has served as the basis of this thesis research, the testing methodology has the potential to benefit other historic structures using amended earthen mortars.

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82 Photomicrographs of Rhoplex™ E-330 amended mortar samples can be seen in Hartzler’s report.
Bibliography


Getty Conservation Institute, "The Earthen Architecture Initiative - Guidelines for the teaching of earthen conservation: Material Analysis - In-Situ and Laboratory Material Characterization."


WUPATKI NATL MONUMENT, ARIZONA (029542), “Period of Record Monthly Climate Summary, Western Regional Climate Center.


Wupatki National Monument


### Wupatki National Monument (029542)

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<th>Month</th>
<th>Avg. Max Temp (°F)*</th>
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* Period of Record: 7/1/1948 to 12/31/2005
Data from Western Regional Climate Center, Wupatki Natl Monument, Arizona (029542)
Appendix B: Research Methodology

Performance Evaluation of Stabilization Mortars

Site Visit

- Studies of Earthen Mortars
  - Stone Wall Construction
    - SW U.S. Outside of U.S.
  - Adobe Wall Construction
    - SW U.S. Outside of U.S.

- Studies of Testing Methods
  - Conditions Assessment
    - Masonry Performance
    - Mortar Performance
  - Analysis & Evaluation of Existing Material
    - Mortar Performance

- Mortar Formulation & Lab Testing
  - Mortar Formulations
    - 1:0 Rhoplex to Water Ratio (by volume)
      - unamended control
    - 1:7 Rhoplex to Water
      - 1:4 Rhoplex to Water
      - 1:3 Rhoplex to Water
  - Physical
    - Wet
    - Dry
      - Consistency
      - Plasticity
      - Shrinkage
      - Water Vapor Permeability
      - Wet/Dry Freeze/Thaw
  - Mechanical
    - Modulus of Rupture
    - Bond/Adhesion

- Historic Repair Mortars
  - Water
  - Qualitative Salts Analysis
    - Microscopy
      - Photomicrographs

- New Stabilization Mortar Soils
  - Particle Size Distribution (granulometry)
    - without sand
    - with sand
      - Particle Size Distribution (granulometry)
      - Micromorphology
      - pH Signature
      - Percent Organics
      - Percent Calcium Carbonate
      - Salt Concentration
      - Clay Mineralogy
      - XRD Microscopy
        - Gravimetric Analysis
        - Acid Digestion

- “Nissan Red” “Mexico”
  - Particle Size Distribution (granulometry)
Appendix C: Sampling and Condition Assessment Locations

North Unit

South Unit
Appendix C: Sampling and Condition Assessment Locations

Sample #1
Appendix C: Sampling and Condition Assessment Locations

Sample #2

WUPA ROOM 36
NORTH WALL INTERIOR (LEFT SIDE)

WUPA_36_N_INT_2
UNKNOWN
Appendix C: Sampling and Condition Assessment Locations

Sample #3

WUPA ROOM 36
NORTH WALL INTERIOR (MIDDLE)
Appendix C: Sampling and Condition Assessment Locations
Sample #4
Appendix C: Sampling and Condition Assessment Locations
Sample #5, 6, 7, 8, 9
Appendix C: Sampling and Condition Assessment Locations
Sample #10, 11
Appendix C: Sampling and Condition Assessment Locations

Sample #12, 13, 14
Appendix C: Sampling and Condition Assessment Locations

Sample #15
Appendix C: Sampling and Condition Assessment Locations

Sample #16

WUPA ROOM 7
NORTH WALL INTERIOR

WUPA_7_N_INT_16
GREY CEMENT
Appendix C: Sampling and Condition Assessment Locations

Sample #17, 18, 19

WUPA ROOM 68
SOUTH WALL INTERIOR

Sample #20, 21

WUPA ROOM 68
SOUTH WALL EXTERIOR
Appendix D: Condition Assessment Survey

North Unit

South Unit
### Condition Assessment: Rooms Completed

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Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 26

WALL ELEVATION: N S E W
   interior   exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended

PRESERVATION MORTAR TYPE(S): 1A 1B 2A 2B 2C 2D 2E
   3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
   other (unamended)

CONDITION OF MORTAR:
durable/secure: eroding; loose, flaking, pitting, cracking, etc.
    2013: surface wall is intact, but lightly friable. Some key loose is
    very friable. 2013 is solid in pack ocher, and friable in other
    (wetting under overhanging rocks)

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.
   No sign erosion

use wall diagram to indicate sample location and annotate conditions
## Appendix D: Condition Assessment Survey

**Center for Architectural Conservation**
**Wupatki National Monument**
**Site Visit: November 13th-14th, 2018**

**Room #:** 7

**Wall Elevation:**
- **N**
- **S**
- **E**
- **W**

**Exposure:**
- **Protected**
- **Exposed**
- **Unprotected**

**Quadrant:**

**Current Mortar Type:**
- Unamended
- Amended:

**Preservation Mortar Type(s):**
- 1
- 2A
- 2B
- 2C
- 2D
- 2E
- 3A
- 3B
- 3C
- 3D
- 3E
- 3F
- 3G
- 3H
- 3I
- 3J
- Other (unamended)

**Condition of Mortar:**
- Durable/secure: eroding; loose, flaking, pitting, cracking, etc.
- Loose, large chunks cracking, mortar crumbled

**Condition of Surrounding Masonry:**
- 3291 - Serious crack
- 3294 - Some minor cracks, weathering, erosion

**Wall in Exit Condition:**
- Better degenerate exposure just degenerating
- Bad

**Stone:**
- Sides, faces, and edges
- Damage due to:

**Note:** Use wall diagram to indicate sample location and annotate conditions.
Appendix D: Condition Assessment Survey

Center for Architectural Conservation  
Wupatki National Monument  
Site Visit: November 13th-14th, 2018

| ROOM #: 36 |
| WALL ELEVATION: | N | S | E | W |
|               |   |   |   |   |
|               |   |   |   |   |
| EXPOSURE:     | protected | semiprotected | unprotected |
| QUADRANT:     |            |              |              |
| CURRENT MORTAR TYPE: | unamended | amended |
| PRESERVATION MORTAR TYPE(S): | 1 | 2A | 2B | 2C | 2D | 2E | 3A | 3B | 3C | 3D | 3E | 3F | 3G | 3H | 3I | 3J |
| CONDITION OF MORTAR:
  durable/secure, eroding, loose, flaking, pitting, cracking, etc.
  Water damage is main deteriorating mech - crumbling or falling masonry lines affected. Many areas of 1216 on north side.

| CONDITION OF SURROUNDING MASONRY:
  differential weathering, cracking, basal erosion, etc.
  Strips cracks in the lap joint of wall (mostly in current)
  Water seeped mortar spalling from southeastern middle of wall. Shall be cleaned before order |

---

**Diagram:**

- Upper Left Quadrant
- Upper Central Quadrant
- Upper Right Quadrant
- Middle Left Quadrant
- Middle Central Quadrant
- Middle Right Quadrant
- Bottom Left Quadrant
- Bottom Central Quadrant
- Bottom Right Quadrant

*Use wall diagram to indicate sample location and denote conditions*
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 36

WALL ELEVATION: N S E W

EXPOSURE: protected semiprotected unprotected

QUADRANT: 

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E 3A 3B 3C 3D 3E 3F 3G 3H 3I 3J other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

SAMPLE TINE

use wall diagram to indicate sample location and annotate conditions
Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 36

WALL ELEVATION: N S E W
- interior
- exterior

EXPOSURE: protected
- semiprotected
- unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended
- amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
- 3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
- other (unamended)

CONDITION OF MORTAR:
durable/secure: eroding, loose, flaking, pitting, cracking, etc.
- 2013 + bottom priming (little cracking)
- 2010 = strange powder while mortars in places

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.
- Poor determination firm current mortars

Use wall diagram to indicate sample location and annotate conditions.
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 32

WALL ELEVATION: N S E W
   interior       exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT: [Diagram showing quadrants]

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
   3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
   other (unamended)

CONDITION OF MORTAR:
durable/secure: eroding, loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

[Diagram showing quadrants]

use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 69

WALL ELEVATION: N S E W
interior exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT: 

CURRENT MORTAR TYPE: unamended amended

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E 2F 2G 2H 2I 2J

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

Diagonals split visible on north side where wall meets
condition of above not great (causing) but no structural problems

Use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 7

WALL ELEVATION: N S E W
- interior
- exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E

2014

3A 3B 3C 3D 3E 3F 3G 3H 3I 3J

other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

- Pitch of 2014 on base of wall solid, other pitch about 1
- Mortar from bottom entirely gone (mortar was exposed underneath)

- Potential recent mortar fill on left side of

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

- Some type of stone used, some new mortar rep

STONE Erosion (Photo # 3A78 - 3A79)

- use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 4

WALL ELEVATION: N S E W
interior exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
2014
3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose; flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

Use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 45

WALL ELEVATION: N S E W
interior exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
other (unamended)

CONDITION OF MORTAR:
durable/secure: eroding, loose, flaking, pitting, cracking, etc.
This section is lightly chipped but mostly in good condition

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

No differential weathering - lentil broken above door but

Use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #:

WALL ELEVATION: N E W

interior exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended:

PRESEvation MORTAR TYPE(S): 1 2A 2B 2C 2D 2E

Cement 90° 90°

3A 3B 3C 3D 3E 3F 3G 3H 3I 3J other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

Use wall diagram to indicate sample location and annotate conditions.
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 7

WALL ELEVATION: N E W
    interior    exterior

EXPOSURE: protected    semiprotected    unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended    amended:

PRESERVATION MORTAR TYPE(S): I 2A 2B 2C 2D 2E
   May 2014 (campaign) 3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
   other (unamended)

CONDITION OF MORTAR: durable/secure; eroding; loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY: differential weathering, cracking, basal erosion, etc.

Sample 15

Use wall diagram to indicate sample location and annotate conditions.
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 7

WALL ELEVATION: N S E W
- interior
- exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E 3A 3B 3C 3D 3E 3F 3G 3H 3I 3J
other (unamended)

CONDITION OF MORTAR:
- durable/secure: eroding; loose, flaking, pitting, cracking, etc.
- matrix mortar (unfilled areas): sloped or areas of 90°
- some cracks visible

CONDITION OF SURROUNDING MASONRY:
- differential weathering, cracking, batal erosion, etc.
- lichen, discoloration, run-off
- too spots on wall

use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 68

WALL ELEVATION: N S E W
   interior    exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
   2015
   White powder
   Unmix
   (no 2016)
   other (unamended)

CONDITION OF MORTAR:
durable/secure: eroding, loose, flaking, pitting, cracking, etc.
   eroding, loose, flaking, pitting, cracking, etc.
   Mortar loss
   Mortar loss
   Mortar loss

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.
   Mortar loss
   Mortar loss
   Mortar loss
   Mortar loss
   Mortar loss
   Mortar loss
   Mortar loss

Use wall diagram to indicate sample location and annotate conditions.
Appendix D: Condition Assessment Survey

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**Center for Architectural Conservation**  
**Wupatki National Monument**  
**Site Visit: November 13th-14th, 2018**

**ROOM #:**  
26

**WALL ELEVATION:**  
- [ ] N  
- [ ] S  
- [x] E  
- [ ] W  
- [ ] interior  
- [ ] exterior

**EXPOSURE:**  
- [ ] protected  
- [ ] semiprotected  
- [ ] unprotected  
- [ ] North unprotected (from wind)  
- [ ] S & W semi-protected

**QUADRANT:**  
- [ ] unamended  
- [ ] amended:

**CURRENT MORTAR TYPE:**  
- [ ] unamended  
- [ ] amended:

**PRESERVATION MORTAR TYPE(S):**  
1  
2A  
2B  
2C  
2D  
2E  
3A  
3B  
3C  
3D  
3E  
3F  
3G  
3H  
3I  
3J  
- [ ] other (unamended)

**CONDITION OF MORTAR:**  
- [ ] durable/secure  
- [ ] eroding/loose  
- [ ] flaking, pitting, cracking, etc.

- [ ] 2013 mortar entirely gone - major water infiltration

**CONDITION OF SURROUNDING MASONRY:**  
- [ ] differential weathering, cracking, basal erosion, etc.

- [ ] Some time showing white haze

---

**Diagram:**  
- [ ] Upper Left Quadrant  
- [ ] Upper Center Quadrant  
- [ ] Upper Right Quadrant  
- [ ] Middle Left Quadrant  
- [ ] Middle Center Quadrant  
- [ ] Middle Right Quadrant  
- [ ] Bottom Left Quadrant  
- [ ] Bottom Center Quadrant  
- [ ] Bottom Right Quadrant

*Use wall diagram to indicate sample location and annotate conditions*
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 63

WALL ELEVATION: N S E W
- interior
- exterior

EXPOSURE:
- protected
- semiprotected
- unprotected

QUADRANT:
- major
- minor
- others

CURRENT MORTAR TYPE:
- unamended
- amended:

PRESERVATION MORTAR TYPE(S):
- 1
- 2A
- 2B
- 2C
- 2D
- 2E
- 7013 (local quarry)
- 20K - cement mix
- others (unamended)

CONDITION OF MORTAR:
durable/secure, eroding, loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

SALT?
- Wave formation (grain, yellow) etc. @ bottom

Use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 32

WALL ELEVATION: N S E W

interior exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E

3A 3B 3C 3D 3E 3F 3G 3H 3I 3J

2016

other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

Damp mortar still largely in place but extremely flaky and
aggregate & coloring on surface

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

Sticky; long wall except southwest face

use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation
Wupatki National Monument
Site Visit: November 13th-14th, 2018

ROOM #: 68

WALL ELEVATION: N S E W
   [Select] interior exterior

EXPOSURE: protected semiprotected unprotected
   [Select] water run-off

QUADRANT: [Select] W N W E

CURRENT MORTAR TYPE: [Select] unamended amended

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E 2F 2G 2H 2I 2J
   [Select] 2016 work
   [Select] other (unamended)

CONDITION OF MORTAR:
durable/secure eroding loose, flaking, pitting, cracking, etc.
   [Select] 2016 year finish with a tear amount of loss (not detect)
   [Select] uniform erosion 10 weeks so water erosion at bottom 5
   [Select] uniform erosion from wind, pre-1900 smooth brown mortar

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.
   [Select] no major rock issues

---

USE WALL DIAGRAM TO INDICATE SAMPLE LOCATION AND ANNOTATE CONDITIONS

---

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Center for Architectural Conservation  
Wupatki National Monument  
Site Visit: November 13th-14th, 2018

ROOM #: 32

WALL ELEVATION: N S E W
   - interior
   - exterior

EXPOSURE: protected semiprotected unprotected

QUADRANT:

CURRENT MORTAR TYPE: unamended amended:

PRESERVATION MORTAR TYPE(S): 1 2A 2B 2C 2D 2E
   - 3A
   - 3B
   - 3C
   - 3D
   - 3E
   - 3F
   - 3G
   - 3H
   - 3I
   - 3J
   - other (unamended)

CONDITION OF MORTAR:
durable/secure; eroding; loose, flaking, pitting, cracking, etc.

CONDITION OF SURROUNDING MASONRY:
differential weathering, cracking, basal erosion, etc.

use wall diagram to indicate sample location and annotate conditions
Appendix D: Condition Assessment Survey

Center for Architectural Conservation  
Wupatki National Monument  
Site Visit: November 13th-14th, 2018

<table>
<thead>
<tr>
<th>ROOM #:</th>
<th>15</th>
</tr>
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<tbody>
<tr>
<td>WALL ELEVATION:</td>
<td>N S E W</td>
</tr>
<tr>
<td>Interior</td>
<td>Exterior</td>
</tr>
<tr>
<td>EXPOSURE:</td>
<td>protected</td>
</tr>
<tr>
<td>QUADRANT:</td>
<td></td>
</tr>
<tr>
<td>CURRENT MORTAR TYPE:</td>
<td>unamended</td>
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<tr>
<td>PRESERVATION MORTAR TYPE(S):</td>
<td>1 2A 2B 2C 2D 2E 3A 3B 3C 3D 3E 3F 3G 3H 3I 3J</td>
</tr>
<tr>
<td>Condition of Mortar:</td>
<td>durable/secure; eroding; loose, flaking, pitting, cracking, etc.</td>
</tr>
<tr>
<td>Condition of Surrounding Masonry:</td>
<td>differential weathering, cracking, basal erosion, etc.</td>
</tr>
</tbody>
</table>

use wall diagram to indicate sample location and annotate conditions
### Sample Information

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_36_E_INT_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Room 36 E Interior</td>
</tr>
<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #1 taken from Room 36 east interior by D. Brown on 12/11/2018. Sample comes from the 2013 campaign.</td>
</tr>
</tbody>
</table>

### Sample Information

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_36_E_INT_1</th>
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</thead>
<tbody>
<tr>
<td>Location</td>
<td>Room 36 E Interior</td>
</tr>
<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>40x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #1 taken from Room 36 east interior by D. Brown on 12/11/2018. Sample comes from the 2013 campaign.</td>
</tr>
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### Sample Information

<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar Sample #2 taken from Room 36 north interior by D. Brown on 12/11/2018. Sample comes from an unknown campaign.</td>
</tr>
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</table>
### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_36_E_INT_2</th>
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</thead>
<tbody>
<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>20x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar Sample #2 taken from Room 36 north interior by D. Brown on 12/11/2018. Sample comes from an unknown campaign.</td>
</tr>
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<table>
<thead>
<tr>
<th>Sample</th>
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<td>Location</td>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar Sample #3 taken from Room 36 north interior by D. Brown on 12/11/2018. Sample comes from the 2016 campaign.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
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<td>Instrument &amp; Software</td>
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<td>Magnification</td>
<td>20x total magnification</td>
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<td>Mortar Sample #3 taken from Room 36 north interior by D. Brown on 12/11/2018. Sample comes from the 2016 campaign.</td>
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Appendix E: Wupatki Mortar Sample Photomicrographs

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<td>Description</td>
<td>Mortar Sample #3 taken from Room 36 north interior by D. Brown on 12/11/2018. Sample comes from the 2016 campaign.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
<td>Location</td>
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<td>Instrument &amp; Software</td>
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<tr>
<td>Magnification</td>
<td>10x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #4 taken from Room 45 west interior by D. Brown on 12/11/2018. Sample is a large aggregate variety dating from the 1990s. Exterior side.</td>
</tr>
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</table>

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</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #4 taken from Room 45 west interior by D. Brown on 12/11/2018. Sample is a large aggregate variety dating from the 1990s. Wall contact side.</td>
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</tbody>
</table>
### Sample Details

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<th>Sample</th>
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<td>Location</td>
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<td>Description</td>
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<td>Description</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
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<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #5 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample comes from the 2014 campaign.</td>
</tr>
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</table>
### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_4_S_INT_5</th>
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<tr>
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<td>Room 4 S Interior</td>
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<tr>
<td>Instrument &amp; Software</td>
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<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #5 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample comes from the 2014 campaign.</td>
</tr>
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<tr>
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<tr>
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<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
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<tr>
<th>Sample</th>
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<tr>
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<tr>
<td>Description</td>
<td>Mortar sample #6 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample is a large aggregate variety dating from the 1990s.</td>
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</table>
## Appendix E: Wupatki Mortar Sample Photomicrographs

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<th>Sample</th>
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<tr>
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<td>20x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar Sample #6 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample is a large aggregate variety dating from the 1990s.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
<td>Location</td>
<td>Room 4 S Interior</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar Sample #7 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample is a large aggregate variety dating from the 1990s.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
<td>20x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #7 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample is a large aggregate variety dating from the 1990s.</td>
</tr>
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</table>
### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_4_S_INT_8</th>
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</thead>
<tbody>
<tr>
<td>Location</td>
<td>Room 4 S Interior</td>
</tr>
<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #8 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample contains cinders and comes from a 1980s campaign.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_4_S_INT_8</th>
</tr>
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<tbody>
<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #8 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample contains cinders and comes from a 1980s campaign.</td>
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### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #9 taken from Room 4 south interior by I. Hough on 12/11/2018. Sample contains cinders and comes from a 1980s campaign.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>Location</td>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>20x total magnification</td>
</tr>
<tr>
<td>Description</td>
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<table>
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<tr>
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<tr>
<td>Magnification</td>
<td>40x total magnification</td>
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<tr>
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### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
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<th>Sample</th>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x total magnification</td>
</tr>
<tr>
<td>Description</td>
<td>Mortar sample #10 taken from Room 7 east interior by I. Hough on 12/11/2018. Sample contains large aggregates</td>
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<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_7_E_INT_10</th>
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<tbody>
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<td>Location</td>
<td>Room 7 E Interior</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Description</td>
<td>Mortar sample #10 taken from Room 7 east interior by I. Hough on 12/11/2018. Sample contains large aggregates</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_7_E_INT_10</th>
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<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
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<td>Description</td>
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<tr>
<td>Sample</td>
<td>WUPA_7_E_INT_11</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
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</tr>
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<td>Instrument &amp; Software</td>
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<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #11 taken from Room 7 east interior by I. Hough on 12/11/2018. Sample is cementitious.</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_7_E_INT_11</th>
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<tr>
<td>Magnification</td>
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<td>Description</td>
<td>Mortar sample #11 taken from Room 7 east interior by I. Hough on 12/11/2018. Sample is cementitious.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #12 taken from Room 7 east interior by D. Brown on 12/11/2018. Sample is a possible 2017 campaign mortar.</td>
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</table>
### Sample Location Instrument & Software Magnification Description

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
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<th>Magnification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WUPA_7_E_INT_13</td>
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<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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</table>
## Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_7_S_INT_15</th>
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<tr>
<td>Location</td>
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<tr>
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<tr>
<td>Description</td>
<td>Mortar Sample #15 taken from Room 7 south interior by I. Hough on 12/11/2018. Sample is from a 2014 campaign.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tr>
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<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar Sample #15 taken from Room 7 south interior by I. Hough on 12/11/2018. Sample is from a 2014 campaign.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_68_S_INT_17</th>
</tr>
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<tbody>
<tr>
<td>Location</td>
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</tr>
<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #17 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from an unknown recent campaign.</td>
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</table>
### Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_68_S_INT_17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
<td>20x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #17 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from an unknown recent campaign.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
<th>WUPA_68_S_INT_18</th>
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<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
<tr>
<td>Magnification</td>
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</tr>
<tr>
<td>Description</td>
<td>Mortar sample #18 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from the 2016 campaign.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>Location</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #18 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from the 2016 campaign.</td>
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</table>
## Appendix E: Wupatki Mortar Sample Photomicrographs

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>Location</td>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<tr>
<td>Magnification</td>
<td>10x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #19 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from an unknown campaign. Wall facing side.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>Location</td>
<td>Room 68 S Interior</td>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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<td>Magnification</td>
<td>10x total magnification</td>
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<tr>
<td>Description</td>
<td>Mortar sample #19 taken from Room 68 south interior by I. Hough on 12/11/2018. Sample is from an unknown campaign. Exterior side.</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
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<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
</tr>
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<td>Magnification</td>
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<tr>
<td>Description</td>
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### Sample Details

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
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<tr>
<td>Instrument &amp; Software</td>
<td>Leica MZ16a stereoscope Nikon DS Fi-1 camera with NIS Elements BR software</td>
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</tr>
<tr>
<td>Description</td>
<td>Mortar sample #20 taken from Room 68 south exterior by D. Brown on 12/11/2018. Sample is from an unknown campaign.</td>
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</table>

<table>
<thead>
<tr>
<th>Sample</th>
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<td>Description</td>
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<table>
<thead>
<tr>
<th>Sample</th>
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<td>Magnification</td>
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<td>Description</td>
<td>Mortar sample #21 taken from Room 68 south interior by D. Brown on 12/11/2018. Sample is from a 2013 campaign.</td>
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## Appendix F: Testing Matrix

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Reference</th>
<th>Total Samples per Test</th>
<th>Shape</th>
<th>Size</th>
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<tbody>
<tr>
<td>Soil Characterization</td>
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<tr>
<td>Appearance</td>
<td>Specifying Color by the Munsell System</td>
<td>ASTM D1535 - 97</td>
<td>2 samples (Moriah w/ &amp; w/o sand)</td>
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<tr>
<td>Appearance</td>
<td>Terminology Relating to Soil, Rock, and Contained Fluids</td>
<td>ASTM D653 - 14</td>
<td>1 sample (Moriah)</td>
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<tr>
<td>Particle Size Distribution</td>
<td>Sieve Analysis of Fine and Coarse Aggregates</td>
<td>ASTM D6913/D6913M - 17</td>
<td>2 samples (Nissan Red, Moriah w/ &amp; w/o sand)</td>
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<tr>
<td>Particle Size Distribution [Wet]</td>
<td>Determining the Amount of Material Finer than 75- μm (No. 200) Sieve by Washing</td>
<td>D1140-17</td>
<td>1 sample (Moriah)</td>
<td>150g</td>
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<td>Percent Organics</td>
<td>Organic Impurities in Fine Aggregates for Concrete</td>
<td>ASTM C40/C40M - 16</td>
<td>1 sample (Moriah)</td>
<td>450g</td>
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<td>Carbonate Content</td>
<td>Calcium (Acid-Soluble) Content; Standard Gravimetric Analysis</td>
<td>Standard Gravimetric Analysis</td>
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<td>pH Signature</td>
<td>pH of Soils</td>
<td>ASTM D4972 - 18</td>
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<td>Clay Minerology</td>
<td>Methylene Blue Adsorption Test</td>
<td>ASTM C1777 - 15</td>
<td>1 sample (Moriah)</td>
<td>60g (No. 200 sieve)</td>
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<td>Salt Concentration</td>
<td>Qual. Soluble Salt Analysis</td>
<td>Merck Test Strips</td>
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<td>20g (No. 10 sieve)</td>
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<td>XRD</td>
<td>X-ray Diffraction (XRD) analysis for qualitative and semi-qualitative clay mineralogy</td>
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<td>1 sample (Moriah)</td>
<td>&lt;10g (No. 200 sieve)</td>
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<tr>
<td>Plasticity</td>
<td>Liquid Limit, Plastic Limit, and Plasticity of Soils</td>
<td>ASTM D4318 - 17</td>
<td>5 samples x 4 formulations</td>
<td>120g (No. 40 sieve)</td>
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<tr>
<td>Mortar Testing</td>
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<tr>
<td>WET: Shrinkage</td>
<td>Linear shrinkage</td>
<td>ASTM C1148 - 92a; ASTM C157</td>
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<td>WET: Shrinkage</td>
<td>Qualitative Visual Shrinkage</td>
<td>yer (2014) and Washa (1960)</td>
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<td>DRY: Water Vapor Permeability</td>
<td>Water Vapor Transmission of Materials</td>
<td>ASTM E96/E96M - 16</td>
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<td>DRY: Wet/Dry</td>
<td>Wetting and Drying Compacted Soil-Cement Mixtures</td>
<td>ASTM D559 - 15</td>
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<tr>
<td>DRY: Freeze/Thaw</td>
<td>Freezing and Thawing Compacted Soil-Cement Mixtures</td>
<td>ASTM D560 - 16</td>
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<td>DRY: Modulus of Rupture</td>
<td>Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading</td>
<td>ASTM D1635/D1635M - 12</td>
<td>5 samples x 4 formulations</td>
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<td>Mock-Up</td>
<td>Tensile Strength of Adhesives by Means of Bar and Rod Specimens; Standard Test Method for Tensile Properties of Adhesive Bonds</td>
<td>ASTM D2095 - 96; ASTM D897-00</td>
<td>5 samples x 4 formulations</td>
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<tr>
<td>Water</td>
<td>Qualitative Soluble Salt Analysis</td>
<td>Merck Test Strips</td>
<td>2 samples</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix G: Testing Manual

Soil Characterization

Particle Size Distribution

Apparatus
- Electronic balance sensitive to 0.1 g
- 8-in. round sieves stack with the following sieves:
  - No. 8 (2360)
  - No. 16 (1180)
  - No. 30 (600)
  - No. 50 (300)
  - No. 100 (150)
  - No. 200 (75)
  - Pan (1)
- Metal scoop
- Mechanical sieve shaker
- Wooden board to level the shaker
- Pre-labelled ceramic evaporating dishes
- Natural bristle brush to transfer materials from the sieves
- Pre-weighed and pre-labelled weighing boats

Procedure
1. Set up the mechanical shaker on top of the wooden board to ensure level testing.
2. Clean all sieves.
3. Measure the appropriate amount of the sampled soil into the evaporating dish.
4. Arrange the sieves in ascending order and tightly wrap with cling wrap.
5. Pour the soil sample slowly into the sieve stack.
6. Place the lid over the top of the sieve stack with more cling wrap.
7. Place the sieve stack on the mechanical shaker and tighten the screw to ensure that the sieve stack is securely fastened to the shaker.
8. Turn on the mechanical shaker and allow to run for ten minutes.
9. Once the mechanical shaker stops, unscrew the sieve stack and remove.
10. Allow the material to settle for five minutes.

Combined Wet and Dry Sieving

Apparatus
- Mortar and rubber-covered pestle
- Balance sensitive to 0.1 g
- Drying oven
- Series of sieves
- Sieve brushes
- Porcelain evaporating dish
- 600mL beaker
- 250 mL cylinder
- Magnetic stirrer
- 4% w/v solution of sodium hexametaphosphate
- Soil hydrometer
- Two hydrometer cylinders (one calibration mark at 1000mL)
- Rubber stopper for 1000mL cylinder
- Thermometer
- Stopwatch
- Plastic wash bottle
- 150 grams of soil
- Deionized water

**Procedure**

**Sample Preparation**

1. Crush approximately 150 g of the sample lightly with a rubber-covered pestle to break down the aggregation of particles.
2. Place the sample in an evaporating dish and dry for 48 hours in a chemically untreated oven maintained at 60°.
3. After drying to constant weight, allow the whole specimen to cool; weight it to the nearest 0.01g.

**Preparation of dispersion treatment**

4. Prepare a standard 4% w/v aq. Solution of sodium hexametaphosphate by mixing 40g of dry material with enough distilled water to make 1000 mL of solution.
   a. Store the solution into a plastic container using a funnel.
   b. The solution should be freshly mixed and never older than one month when used.

**Pre-Treatment/Dispersion of Sample**

5. After weighing, transfer the dried and crushed soil sample to a 600mL Pyrex beaker and cover with about 200mL of the 4% solution.
6. Stir until the soil is completely wet and allow to stand for at least one hour.
   a. Or over night
7. After the standing period, complete the dispersion of the particle by using a magnetic stirrer at a medium velocity for 15 minutes using a PTFE coated stir bar. Cover the beaker with a watch glass.
   a. Note the weight of the stir bar before and after each test to measure loss of stir bar coating.

**Wet Sieving/Washing**

8. Transfer the soil and solution to a 75 µm (No. 200) stainless sieve nested on a basin.
9. Carefully wash the soil with a jet of distilled water until all fine material is washed through the sieve; i.e. until the water is clear. The amount of water should not exceed to 500mL. Be extremely careful not to lose any soil by splashing the material out of the sieve of by allowing the water to overflow the container.
10. Set aside the material collected in the basin for use in the sedimentation test.

**Backwashing**

11. By backwashing, transfer the material retained on the 75 µm (No. 200) sieve to a weighed evaporation dish.
12. Let the material stand until the top of the suspension becomes clear. This may take several hours.
13. Pour off as much clear water as possible into a beaker.
14. Place the dish with the remaining soil/water suspension in the untreated oven (60°) for drying.

**Dry Sieving**
15. When the material in the evaporating dish is dry, allow it to cool and weight it.
16. Run the sample through a small US Standard sieve stack
17. Record the weights of the individual samples from the different sieves to the nearest 0.01 g.

**Sedimentation**
18. Add the any material that passed through the 75 µm (No. 200) to the material for the sedimentation test.
19. Take the suspension of the pretreated soil which passed the 75 µm (No. 200) sieve in the wet and dry sieving and transfer to one of the 1000 mL sedimentation cylinders.
20. Fill the second cylinder—the control cylinder—with distilled water.
21. The distilled water temperature was adjusted so that all the cylinders were at the same temperature.
22. Cap the sedimentation cylinder with a rubber stopper to obtain a watertight fit.
23. Carefully shake the cylinder to obtain a uniform suspension.
24. Invert the cylinder for a few seconds and then place it upright.
25. Start timing.

**Readings**
26. Remove the rubber stopper and inset the hydrometer to take readings from the sedimentation cylinder and the control cylinder.
27. Take readings at the top of the meniscus after ½, 1, 2, and 4 mins.
28. After the fourth reading, reposition the rubber stoppers on the sedimentation cylinder and reagitute.
29. Take readings at the top of the meniscus after ½, 1, 2, and 4 mins.
30. Repeat process four times, until two sets of readings agreed with one unit of each other for all four readings.
31. When agreement between readings is reached, take additional readings at the top of the meniscus at elapsed time of 8, 15, 30, and 60 minutes, then at 2, 4, 8, 16, 32, 64, 96, hours, roughly.
   a. Regular readings are not necessary as long as the time of each reading is carefully record on the data sheet.
32. Take temperature readings to the nearest 1°C for each hydrometer reading.

**Plastic Limit, Liquid Limit, and Plasticity Index**

**Apparatus**
- Spatula (blade about 75mm 20mm)
- Balance sensitive to 0.1g
- Drying oven
- Surface for rolling: ground glass plate or non-absorbent paper
- Soil sample containers (metal, with lids)
- Evaporating dish
- 3mm glass rod for gauging diameter
- Casagrande device and grooving tool (ASTM D4318-17)
- Mortar and rubber-covered pestle
- Deionized water
- 120g of soil that has been sieved through a 425 µm screen
**Procedure**

**Preparation**
1. Take air dried soil and break up the aggregations of soil using the mortar and rubber-covered pestle.
2. Sieve the soil through a 425 µm sieve (No. 40) nested on a receiving pan. About 120 grams of sieved dry soil is necessary for the two tests.

**Testing for Plastic Limits**
1. Take about 15-20 grams of the soil sample that has passed through the 425 µm (No. 40) sieve.
2. Place the air-dried soil in an evaporating dish and thoroughly mix with distilled water until the mass becomes plastic enough to be easily shaped into a ball without sticking to the fingers excessively when squeezed. Take a portion of this ball weighing about 8 g (or about half of the sample) for the test sample.
3. Squeeze and form the 8 g test sample into a round ellipsoidal-shaped mass. Roll the sample between the fingers of one hand (which should be clean and free from grease) and the glass plate which should be lying on a smooth horizontal surface. Use enough pressure to roll the mass into a thread of uniform diameter across its length. Move your hand with fingers outstretched across the sample to develop this uniformity in diameter. The rate of rolling should be between 80 and 90 strokes per minute. A stroke is counted as one complete motion of the hand forward and back to starting position again. The pressure should reduce the diameter of the thread to about 3 mm between 5 and 10 strokes. It is important to maintain a uniform rolling pressure as the thread approaches 3 mm.
4. When the diameter of the thread becomes 3mm (use the glass rod as a guide), break the thread into 6 or 8 pieces. Squeeze these pieces together between thumbs and fingers of both hands into a rough ball and repeat the entire process.
   a. Water from the sample is evaporating into the air and the sample is becoming progressively drier
5. Continue this alternate rolling to a 3 mm diameter thread, gathering together, kneading and re-rolling until the thread crumbles under the pressure required for rolling and the soil can no longer be rolled into a thread.
   a. The crumbling may occur when the thread has a diameter greater than 3 mm. This should be considered a satisfactory endpoint, provided the soil has been previously rolled into a 3 mm thread (If the thread breaks before it has initially been rolled down to the 3 mm diameter, the moisture content is less than that for the plastic limit and more water should be added to the sample).
6. When the plastic limit has been reached, place the crumbled soil samples in a numbered and weighed moisture sample container. Cover the container immediately to avoid change in weight of the sample by evaporation.
7. Weigh the container and the soil and record the combined mass. Place the container, with the cover removed, in a 60° C oven and dry to a constant mass (usually 24-hours).

**Testing for Liquid Limit**
1. Adjust the Casagrande device.
2. Take about 100 grams of the sample material that has passed the 425 µm (No. 40) sieve.
3. In an evaporating dish, thoroughly mix the soil sample with 15-20 ml of distilled water by alternately stirring, kneading, and chopping with a spatula. Add more water, in increments of 1-3mL, until the sample is a thick, homogenous paste.
4. Make sure the cup of the Casagrande device rests on the base. Place a portion
   of the mixed sample in the cup. Using the spatula, press it from the middle
   outwards to prevent trapping any air bubble in the mass. Use as few strokes as
   possible. Level the surface of the soil paste again (again using the spatula) and
   trim it to a depth of 1 cm at the point of maximum thickness. Return excess soil to
   the evaporating dish.
5. Divide the soil in the cup into two equal halves by firm strokes of the grooving tool
   along the centerline. Starting near the hinge, draw the grooving tool towards the
   front in a continuous motion, always keeping the tool normal to the surface of the
   cup.
6. Lift and drop the cup by turning the crank handle at a rate of two revolutions per
   second. Continue turning until the groove is closed along a distance of 13 mm.
   The back end of the standard grooving tool serves as a gauge length
7. Record the number of drops required to reach this condition.
8. Remove a slice of soil approximately the width of the spatula, extending from
   edge to edge of the soil cake at a right angle to the groove where the two
   portions flowed together. Place in a weighed sample container. Cover the
   sample container, and weigh and record the combined mass on the data sheet.
9. Place the sample container with the cover removed in a 60° C oven. Oven dry
   the soil to constant mass (overnight). Remove the sample container form the
   oven and place the cover on the container to cool at room temperature. Weigh
   the sample again and record the mass. Record the loss in mass due to drying as
   the mass of water.
10. Transfer the soil still in the cup to the remaining soil paste in the evaporating dish.
    Wash and dry the cup, grooving tool, and spatula, Reattached and adjust the
cup for the next trial.
11. Repeat process at least three more times with the soil collected in the
    evaporation dish, adding a little more water each time. The object of this
    procedure is to obtain samples of such consistency that the number of drops
    required to close the groove will be roughly evenly space over the range from 50
to 100.
12. Calculate the water content of the soil for each drop count.

Qualitative Soluble Salt Analysis

Apparatus
- MQuant Nitrate test strips
- MQuant Chloride test strips
- MQuant Sulfate test strips
- Approximately 20 g of material that has been sieved through a 200 µm (No. 10
  sieve)

Procedure
1. Sieve approximately 20 g of material through the 200 µm (No. 10 sieve)
2. Soak 10g of the soil in 10 mL of deionized water for three hours to bring any soluble
   salts into solution
3. Immerse test strips into the solution and observe for color changes in the indicators
   on the strips
Quantitative Organic Content Analysis

Apparatus
- Bottles—colorless glass or plastic graduated bottle, approximately 240 to 470-mL [8 to 16-oz], equipped with watertight stoppers or caps, not soluble in the specified reagents
- Standard Color Solution Level—75 mL [2.5 oz]
- Fine Aggregate Level—130 mL [4.5 oz]
- NaOH Solution Level—200 mL [7 oz]
- 450 g of soil

Procedure
1. Fill a glass bottle to approximately 130-mL [4.5-fluid oz] level with the sample of the fine aggregate to be tested.
2. Add the sodium hydroxide solution until the volume of the fine aggregate and liquid, indicated after shaking, is approximately 200 mL [7 fluid oz.]
3. Stopper the bottle, shake vigorously, and then allow to stand for 24 hours.
4. Prepare the Standard Color Solution by dissolving reagent grade potassium dichromate (K₂Cr₂O₇) in concentrated sulfuric acid at a rate of 0.25 grams K₂Cr₂O₇ per 100 ml of acid using gentle heat if necessary to effect solution.
5. At the end of the 24-h standing period, fill a glass bottle to the approximately 75-mL [2.5-fluid oz] level with the fresh standard color solution, prepared not longer than 2 h previously.
6. Hold the bottle with the test sample and the bottle with the standard color solution side-by-side and compare the color of light transmitted through the supernatant liquid above the sample with the color of light transmitted through the standard color solution. A color lighter than that of the standard solution indicates a negligible amount of organic material present in the soil sample while degrees of color in the supernatant liquid that are darker than the standard solution indicate the presence of significant organic content in the soil.

Calcium (Acid-Soluble) Content

pH Signature
Soil pH was measured according to ASTM D4972-18, Standard Test Methods for pH of Soils.1 The basis for this test was Method B which measure pH using pH sensitive paper. This method provides an approximate estimate of the pH of the soil.

Apparatus
- Glass beaker
- pH test strips
- Approximately 20 g of material that has been sieved through a 200 µm (No. 10) sieve.

Procedure
1. Take about 10 grams of the soil sample that has passed through the 200 µm (No. 10) sieve.
2. Weigh and record the mass to the nearest 0.1 g.

3. Soak 10 grams of the soil in 10 mL of deionized water
4. Immerse pH indicator test strips into the solution and match the color

**Apparatus**
- Oven
- Desiccator
- Balance sensitive to 0.1 g
- 600 mL beaker
- 500 mL Erlenmeyer flask
- Magnetic stirring plate
- Magnetic stir bar and retriever
- 24 cm glass funnel
- 24 cm filter paper
- Instrument stand
- Watch glass

**Procedure**

**Preparation**
1. Collect approx. grams of the sample that has been dried and place in a 600 mL beaker.
2. Slowly add the 14% solution of hydrochloric acid with approximately 250 mL.
3. Record the weight of the stir bar.
4. Place the beaker with sample and acid on mechanical stirring place.
5. Agitate for no more than 24 hours, leaving a watch glass on top of the beaker.
6. Reweigh the stir bar after dissolution is complete.

**Separation/Filtration/Sieving**
1. Record and label the 24 cm diameter filter paper
2. Fold the paper into quarters and place it in a large funnel held in place by a funnel support on an instrument stand.
3. Position the funnel so that it will drain into a large 500 mL.
4. Prewet the filter paper with deionized water.
5. Add a few drops of hydrochloric acid to the beaker containing the sample to verify complete acid digestion.
6. Slowly add deionized water to the remaining sample material. Wash down the sides of the glass rod and inside the beaker.
7. Swirl with a glass rod to levigate the fines.
8. Slowly pour the liquid with suspended material through the filter, being careful to keep the heavier solid particles (aggregate) at the bottom of the beaker.
9. Repeat process until the beaker is clear.
10. Dry the fines on the filter paper at 60°C in a chemically treated oven for 24 hours. Place in desiccator on a watch glass.
11. Wash the sand with water several times and leave it to dry for 24 hours in a 60°C chemically treated oven.
12. Weigh the filter paper with the dry fines to determine the weight of the fines.
13. Weigh the dry aggregate and record the weight.
14. Express the amount of aggregate as a w/w (weight-to-weight) percentage of the whole sample/Express the fines in the same manner. The amount of dissolved material is calculated by summing up the percentages of sand and fines and subtracting from initial weight of the sample x 100%.
Methyl Blue Adsorption test

**Apparatus**
- electronic balance
- 500 mL Pyrex glass beaker
- 600 mL Pyrex beaker
- Pre-labelled filter papers
- 0.01 concoction of methylene blue solution
- Deionized water
- Glass rods
- Chemical spatula
- Plastic container for methylene blue solution
- Funnel
- Approximately 60 g of oven dried soil sample that has passed a 75 µm (No. 200) sieve

**Procedure**
A fresh batch of methylene blue solution should be prepared prior to the test day.

*Preparation of Methyl Blue solution*
1. The methylene blue agent used for this test was made of a concentration of 10g/L with about 10 g of HMP compound measured into a 600 mL Pyrex glass beaker
2. Pour 500 mL of deionized water into the beaker and stir using an 8mm glass rod until the entire compound is dissolved. Pour the solution into a plastic container using a funnel.
3. Pour 500 mL of deionized water into the beaker to ensure that the HMP is thoroughly dissolved in the deionized water and then pour into the plastic container.

*Testing Procedure*
1. Place approximately 60 g of oven dried soil that has passed through a No. 75 µm (No. 200) in a beaker with 500ml of deionized water and disperse within the water using a glass rod.
2. Add the methylene blue solution to the dispersed sample in unit doses of 5 ml of 0.01 conc.
3. After each addition of 5 ml dose of methylene blue, collect a small quantity of the suspension with a glass rod and place onto standard filter paper, producing a dark blue stain.
4. Add extra doses of methylene blue to the sample until a light blue halo forms in the wet area around the stain.
5. Once a light blue halo is observed on the filter paper, stop adding methylene blue to the sample.
6. Check the sample again at one-minute intervals to determine the stability of the halo.
7. When the halo persists after five minutes, the test will be considered complete.
8. Once the test is completed, calculate the total amount of methylene blue solution used for the experiment.
Mortar Performance Testing

Mortar Mixing

Apparatus
- Hobart C-100, 3-speed mechanical mixer
- Rubber spatula
- Plastic sheet
- Timer
- Sieve No. 8

Procedure
1. Sieve soil through a No. 8 sieve to ensure large clumps and extraneous materials are removed.
2. Combine sand and soil in the mixer on slow speed for 60 seconds. Stop the mixer.
3. Add ½ of the Rhoplex to water liquid.
4. Mix on medium speed for 30 seconds. Stop the mixer.
5. Scrape down the sides of the mixer and allow the mixture to stand for 90 seconds.
6. Add the rest of the liquid.
7. Mix on medium speed for 60 seconds. Stop the mixer.

Consistency (Slump Test)

Apparatus
- Flow table and flow mold conforming to ASTM C230
- Caliper
- Tamping rod
- Trowel with steel blade

Procedure
1. Wipe down the flow table clean and try, and place the mold at the center.
2. Place a layer of mortar about 25 mm in thickness in the mold and tamp 20 times with the tamper to ensure uniform filling of the mold.
3. Fill the mold with mortar and tamp as specific with the first layer.
4. Cut off the mortar to a plane surface flush with the top of the mold by drawing the straightedge (trowel) across the top of the mold using a sawing motion.
5. Wipe the table top clean and dry, being especially careful to remove any water from around the edge of the flow mold.
6. Lift the mold away from the mortar 1 min after completing the mixing operation.
7. Immediately drop the table 25 times in 15 s.
8. Measure the diameter of the mortar along the four lines scribed in the table top, recording each diameter as the number of caliper divisions, estimated to one tenth of a division.

Linear Drying Shrinkage Test

**Apparatus**
- Wooden molds, of 1”x1”x6-¼ ”
- Mineral oil
- Tamper
- Trowel
- Caliper

**Procedure**
1. Measure the original length of the earthen mortars.
2. Remove the specimens from the molds after they have completely dried.
3. Use the comparator to calculate the length change of the specimen

Qualitative Visual Shrinkage

**Apparatus**
- Un-glazed terracotta saucers
- Trowel

**Procedure**
1. Apply the mortar into the un-glazed terra cotta saucers with a trowel.
2. Use the trowel to scrape off excess and insure the sample has filled the saucer to the brim.
3. Set the samples to dry in the baker’s rack.
4. Observe for shrinkage cracks after samples have completely dried.

Durability: Wet/Dry Resistance

**Apparatus**
- 20 samples of earthen mortar cast in 1.5”x1.5” cylindrical molds
- Soaking container
- Sheet pan
- Drying oven
- Timer

**Procedure**
1. Soak cylinders in ambient temperature deionized water for five hours,
2. Dry the samples overnight in an oven at approximately 90°C.
3. Note the condition and weight of the soil cylinders at the end of each drying cycle.

Durability: Freezing/Thawing

**Apparatus**
- 20 samples of earthen mortar cast in 1.5” x 1.5” cylindrical molds
- Absorbent felt pads
- Tray to hold samples
**Procedure**

1. Place cylinders of mortar on an absorbent pad that is saturated in water.
2. Samples are cycled through freezing (at approximately -5° to -10°C) for 24 hours and thawing (at ambient laboratory temperatures) for 24 hours, always remaining moist.
3. Note the change in condition of the soil cylinders at the end of each thawing cycle.
4. Turn the specimens over on end after each thawing cycle.

**Water Vapor Permeability**

**Apparatus**
- 3” x .75” cylindrical PVC molds
- Disposable plastic beaker (250ml)
- Balance sensitive to 0.01g
- Water vapor transmission chamber (desiccator)
- Paraffin wax
- Hot plate
- Small glass rod
- Electrical tape
- Desiccator chamber
- Deionized water

**Procedure**

1. Weigh the sample.
2. Line the sample with electrical tape on the outer edge.
3. Fill the beakers with 100 ml of deionized water.
4. Seal the disks of amended soil in the open tops of plastic beakers by melting paraffin on the hot plate and dropping the liquid paraffin around the rim of the beaker.
5. Weigh the test assembly and place in the desiccator along with calcium sulfate desiccant.
6. Weigh the beakers daily and change the desiccant regularly.

**Modulus of Rupture**

**Apparatus**
- 20 samples of rectangular prisms with dimensions of 1.0” w x 1.0” d x 6.25” l
- Instron Universal Testing Machine, model 4206

**Procedure**

- Measure the prism samples specific dimensions (width, depth, length).
- Load dried samples into the testing machine to calculate the modulus of rupture.
### Particle Size Distribution--Moriah

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<th>Sieve No.</th>
<th>$M_{5x}$</th>
<th>%M</th>
<th>%M</th>
<th>%M</th>
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<td>100.00%</td>
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<td>12.84%</td>
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### Particle Size Distribution--Moriah (with sand)

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### Particle Size Distribution--Nissan Red

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Particle size distribution of the Moriah and Nissam Red soil was determined using a mechanical sieve. Source: Dickensheets 2019.

<table>
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<th>Soil Type (Particle Gradation)</th>
<th>Coarse Sand</th>
<th>Medium Sand</th>
<th>Fine Sand</th>
<th>Fines</th>
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<td>Moriah</td>
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<tr>
<td>Moriah w/ sand</td>
<td>13.32%</td>
<td>31.49%</td>
<td>48.14%</td>
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The soil and solution were transferred to a 75 μm (No. 200) stainless sieve nested on a basin. Source: Dickensheets 2019.

By backwashing, transfer the material retained on the 75 μm (No. 200) sieve was transferred to a weighed evaporation dish. Material was allowed to stand until the top of the suspension becomes clear which took several hours. Source: Dickensheets 2019.

<table>
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<th>Correction, Reading, Rc</th>
<th>Effective Depth (cm)</th>
<th>L/T</th>
<th>K</th>
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Particle size distribution of the Moriah soil after dry sieving. Source: Dickensheets 2019.
### Soil Particle Description (Moriah)

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**Instrument & Software**
Leica MZ16a stereoscope
Nikon DS Fi-1 camera with NIS Elements BR software

### Appendix H: Soil Characterization

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**Instrument & Software**
Leica MZ16a stereoscope
Nikon DS Fi-1 camera with NIS Elements BR software

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### Soil Particle Description (Moriah)

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### Soil Particle Description (Moriah)

#### Instrument & Software
- Leica MZ16a stereoscope
- Nikon DS-Fi1 camera with NIS Elements BR software

#### Magnification
- 100x total magnification

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## Plastic Limits

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<th>Samples</th>
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<th>Dry Weight (g)</th>
<th>Water Content (g)</th>
<th>Plastic Limit</th>
<th>Average</th>
<th>Median</th>
<th>Std. Dev.</th>
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### Liquid Limits

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<td>9.35</td>
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</table>
Soils were stirred into solution, after sitting for one hour the Merck strip was placed into the solution. Source: Dickensheets 2019.

Organic Content Test

The organic content test resulted in no color change when the soil sample was allowed to stand in the sodium hydroxide solution for over 24 hours. This indicates the absence of organic material. Source: Dickensheets 2019.
The carbonate content of the soil samples was tested using digestion by acid (15% hydrochloric acid solution). Fines were collected on filter paper (seen on right). Source: Dickensheets 2019.

<table>
<thead>
<tr>
<th>Dry Sample Mass (g)</th>
<th>Mass after Acid Digestion (g)</th>
<th>Mass of Acid Soluble Fraction (g)</th>
<th>% Acid Soluble</th>
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<tr>
<td>29.83</td>
<td>28.33</td>
<td>1.48</td>
<td>4.96%</td>
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</table>

Methylene Blue Absorption Test

After preparing the 10g/L methylene blue solution, 5ml doses of methylene blue trihydrate were added with a glass rod, and a drop placed onto filter paper. Source: Dickensheets 2019.
X-Ray Diffraction testing was performed at the University of Pennsylvania’s Laboratory for the Research of Structural Matter using a Rigaku MiniFlex™ benchtop powder X-ray diffraction instrument. Moriah soil that had passed through the No. 200 sieve was packed into a sample container and placed into the machine. Source: Magill 2019.
Appendix I: Mortar Performance Testing

Rhoplex E-300 formulations were prepared ahead of time and stored in plastic containers. Source: Dorcas Corchado 2019.

ASTM C305-14 was modified to standardize a procedure for all earthen mortar formulations. A Hobart C-100 mechanical mixer was used. Source: Kallie Kothmann 2019.

Slump Test

The slump test provides a quantitative indicator of a mortar’s consistency. To measure slump, a flow table in compliance with ASTM C230 is used. This photo illustrates the slump of an earthen mortar following testing. Source: Dickensheets 2019.
Terra cotta saucers were filled with the earthen mortars and allowed to dry in order to observe shrinkage. Source: Dickensheets 2019.

Shrinkage is seen through cracking and the separation of the earthen mortars from the edges of the saucer. Source: Dickensheets 2019.
Wooden molds were coated with mineral oil prior to the mortar being placed inside. The difference in length was measured with the mold length as the initial (wet) length and the final mortar sample length as the final (dry) length. Source: Dickensheets 2019.

### Linear Shrinkage

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<th>L (final length)</th>
<th>S (% shrinkage)</th>
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<th>Median</th>
<th>Std. Dev.</th>
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<td>0.45%</td>
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<td>6.0</td>
<td>4.22%</td>
<td></td>
<td>4.18%</td>
<td>0.45%</td>
</tr>
<tr>
<td>1:0 E</td>
<td>6.3</td>
<td>6.0</td>
<td>3.98%</td>
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<td>4.22%</td>
<td>0.45%</td>
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<td>1:7 A</td>
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## Durability: Wet/Dry Resistance

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<th>% Lost</th>
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</table>
Earthen mortar samples were submerged in distilled water for five hours before being dried in an oven. Source: Dickensheets 2019.

Unamended earthen mortar samples (top row) completely dissolved during the first cycle. Source: Dickensheets 2019.

Amended earthen mortar samples after the third wet/dry cycle. Flaking and particle disintegration is seen on the samples of all Rhoplex concentrations. Source: Dickensheets 2019.
Amended earthen mortar samples after the third wet/dry cycle. Crisp edges are maintained on many of the samples. Source: Dickensheets 2019.

Amended earthen mortar samples after the third wet/dry cycle. Crisp edges are maintained on many of the samples. Source: Dickensheets 2019.

Amended earthen mortar sample containing the lowest concentration of Rhoplex after twelve wet/dry cycles. Crisp edges along the sample’s upper perimeter are maintained. Source: Dickensheets 2019.
Appendix I: Mortar Performance Testing  

Amended earthen mortar sample containing the highest concentration of Rhoplex after twelve wet/dry cycles. Source: Dickensheets 2019.

Amended earthen mortar sample containing the lowest concentration of Rhoplex after twelve wet/dry cycles. This was one of the worst performing samples. Source: Dickensheets 2019.

Amended earthen mortar sample after twelve wet/dry cycles. Crisp edges along the sample’s upper perimeter are somewhat maintained but material is flaking away. Source: Dickensheets 2019.
Freeze/Thaw Resistance samples prior to testing. There are five samples for each concentration of Rhoplex. All samples were subjected to twelve freeze/thaw cycles. Source: Dickensheets 2019.

Freeze/thaw resistance samples were placed on an absorptive felt pad that allowed them to draw up water and remain moist throughout the testing process. Source: Dickensheets 2019.

Samples after the 3rd freeze cycle, pre-thaw. Unamended samples are seen in the first row and display the greatest amount of “slump”, particularly in the sample seen on the far left. Amended samples (1:7 in the second row, 1:4 in the third row, 1:3 in the back row) also exhibit signs of deterioration as the bases expand due to the water entering the sample. There does not appear to be a major difference between the different formulations of Rhoplex and performance. Source: Dickensheets 2019.
Sample after the 3rd freeze/thaw cycle, post thaw. The collection of disintegrated aggregate can be seen at the base of the samples. The unamended mortar samples display the greatest amount of shape deformation and aggregate loss. Source: Dickensheets 2019.

All earthen mortars experience shape deformation in the form of slumping and granular loss that was collected on the absorbent pad. Source: Dickensheets 2019.

An unamended earthen mortar sample after the twelve freeze/thaw cycles. Significant shape deformation and material loss had occurred in comparison to the amended earthen mortars. Source: Dickensheets 2019.
Appendix I: Mortar Performance Testing


After twelve freeze/thaw cycles. One of the best performing samples was an amended earthen mortar containing a ratio of 1:3 Rhoplex to water (by volume). Significantly less deformation and material loss than the unamended. Source: Dickensheets 2019.

After twelve freeze/thaw cycles. Amended samples still faced deformation and material loss but to a lesser degree than the unamended. Source: Dickensheets 2019.
Earthen mortar samples that were also used for the linear shrinkage test were also used for the modulus of rupture. Additional samples were made to test the machine prior to collecting data for the sample cohorts. Source: Dickensheets 2019.

Sample after testing. The brittleness of the samples resulted in no plastic deformation so that when the broken halves are matched up, they fit exactly into place. Source: Dickensheets 2019.

Sample after testing on the Instron 4206 machine. The two blunt-edged knives were spaced two inches apart for all of the samples. Source: Dickensheets 2019.
## Modulus of Rupture

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Appendix I: Mortar Performance Testing

Modulus of Rupture

1:0 Sample A

1:0 Sample B

1:0 Sample C
Appendix I: Mortar Performance Testing

Modulus of Rupture

1:0 Sample D

1:0 Sample E

1:7 Sample A
Appendix I: Mortar Performance Testing

Modulus of Rupture

1:7 Sample B

Load (lbs) vs. Displacement (in)

1:7 Sample C

Load (lbs) vs. Displacement (in)

1:7 Sample D

Load (lbs) vs. Displacement (in)
Appendix I: Mortar Performance Testing

Modulus of Rupture

1:7 Sample E

1:4 Sample A

1:4 Sample B

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Appendix I: Mortar Performance Testing

Modulus of Rupture

*The Gravity Load (G.L.) was not reset prior to testing, its results are not included in the sample cohort’s averages.

1:4 Sample C

1:4 Sample D

1:4 Sample E
Appendix I: Mortar Performance Testing

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