# TESTING AND EVALUATION OF SOIL BASED GROUTS FOR THE ADHESION OF CONSOLIDATED AND UN-CONSOLIDATED PAINTED LIME PLASTER AT THE MISSION SAN JOSE DE TUMACÁCORI.

Nicole Mariel Declet Díaz

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania
In Partial Fulfillments of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2017

______________________

Advisor

Frank G. Matero

Professor of Architecture

______________________

Program Chair

Randall F. Mason

Associate Professor and Chair, Historic Preservation

## Acknowledgments

First, I would like to thank my thesis advisor, Frank G. Matero for suggesting such a wonderful topic, and for the opportunity to work with such an outstanding structure, The Mission San José de Tumacácori. His guidance and encouragement during this process was invaluable. I would also like to thank the U.S. National Park Service, and the Tumacácori National Historic Park's staff, in particular, Alex B. Lim, for all of his help in acquiring materials for this testing program.

Thank you to the ACL Staff for providing access to all their background information on Tumacácori. I am very appreciative of Courtney Magill, for her ongoing support and assistance in making sure I had everything I needed to perform testing for this research.

I would also like to thank my classmates, the HPSV Class of 2017, in particular Araba Prah for her support during the long nights in the laboratory and for her assistance during testing. Special thanks to Nityaa Iyer for responding promptly to questions regarding her wonderful research on soil grouts.

Finally, I am extremely thankful to my family and friends for providing me immense joy and support.

## Contents

## List of Figures:

## List of Tables:

# Chapter 1: Introduction

The interior painted plaster finishes of Mission San José de Tumacácori are a rare survival of late 18th century-early 19th century artistic traditions of northern Sonora and the Kino mission churches. Despite earlier attempts to stabilize these interior finishes, the original painted lime plaster has continued to detach from the adobe substrate.[1]

The current research evaluates soil-based injection grouting in order to re-adhere the detached plaster from its adobe substrate. Earthen grouts were chosen over the more commonly used hydraulic lime grouts in order to consider a more compatible system with the original adobe substrate. A well-designed earthen grout must be fluid enough to insure good injectability and full void penetration, exhibit low shrinkage, and strong bond strength equal to its own cohesive strength for successful repair.

Samples of the original adobe, mortar, and plaster were analyzed and local soils were sampled and tested in order to design a grout displaying optimal properties. The proposed grout formation made use of 2% sodium hexametaphosphate (HMP) in the mixing water. HMP is a common ingredient for sedimentation processes in soil analysis and has been employed to reduce shrinkage and viscosity in earthen grouts (Silva and Oliveira 2009; Silva et al. 2012; Lourenco et al. 2013; Iyer 2014). The test grout was subjected to several geo-technical tests including viscosity, density, shrinkage, and

[1] Previous techniques to conserve the paintings began with research by J. Rutherford Gettens in 1949-1952 and subsequent attempts in 1984 to reattach detached plaster have proven ineffective. The last time exhaustive work was done in the interior nave was in 1984.

expansion/ bleeding; as well as its hardened properties such as splitting tensile strength, capillary water absorption, water retention and permeability.

The selected grout's performance was finally analyzed within a mock-up assembly composed of friable plaster facsimiles and adobe, simulating 1/2" and 1/4" gaps. Half of the plaster facsimiles were consolidated with nanolime due to their friable nature based on recent complementary research (Jang 2016). The research expands current knowledge on the use of earthen grouts for reattachment of earthen and lime plasters on earthen substrates.

# Chapter 2: Context

## 2.1 Mission San José de Tumacácori History

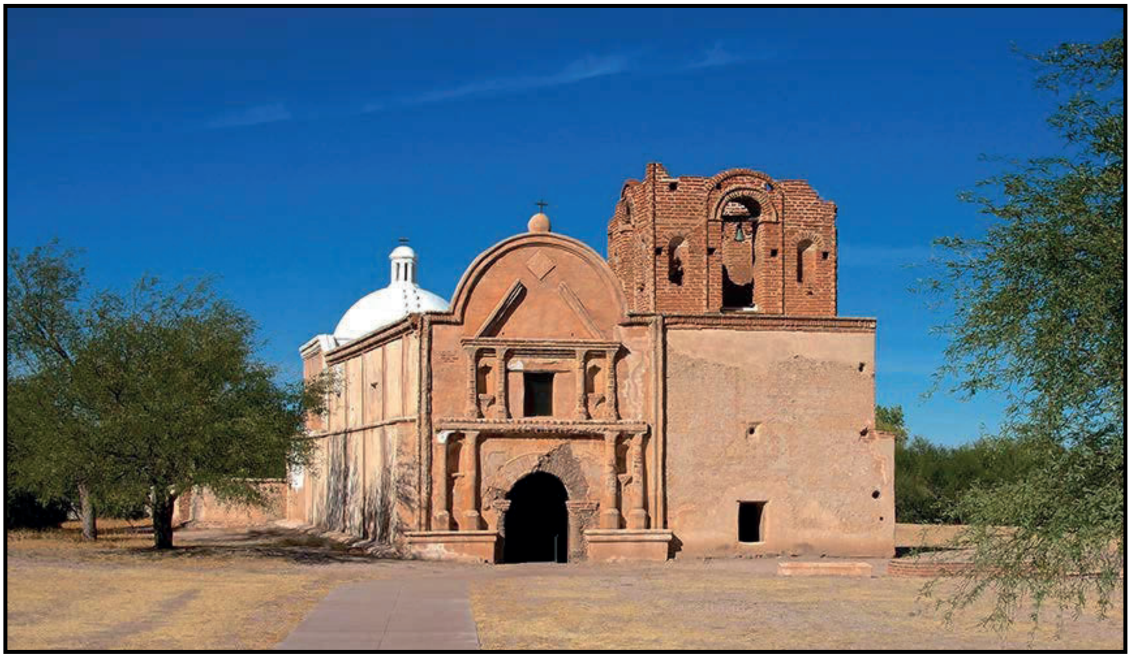
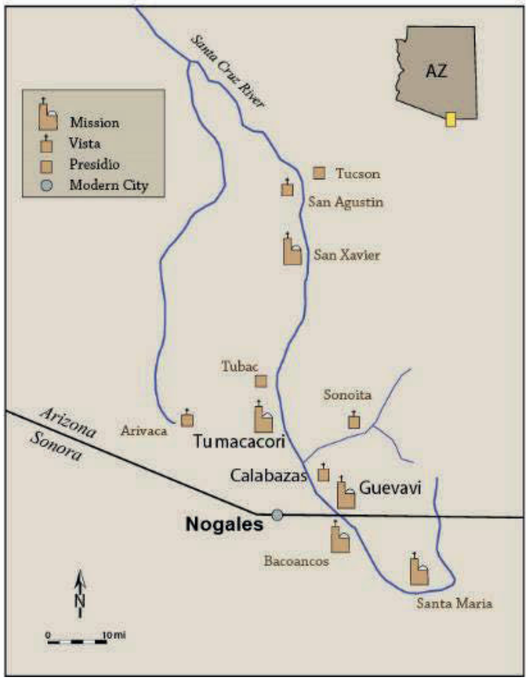


Figure 1: Present day Mission San José de Tumacácori. Source: Unknown photographer. National Park Service.

The Mission San José de Tumacácori is one of two Spanish-Colonial buildings to be designated a National Monument in 1908 by President Roosevelt under the Antiquities Act (Moss 2008, 3). The site became a National Historic Park in 1990, 72 years after federal management. Today, the structure stands amid a 360 acre park, located south of Tucson, Arizona within the Santa Cruz River Valley. Unlike other Spanish Colonial missions within the United States, Tumacácori was never completed and its belltower remains unfinished to this day.



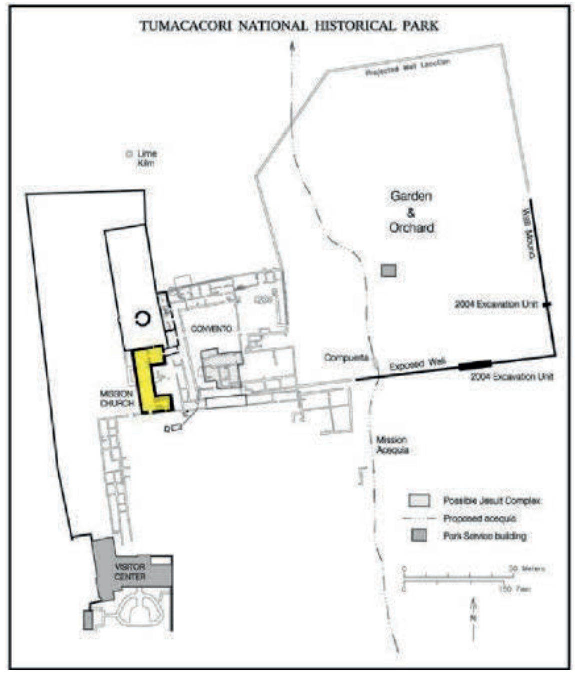




Figure 2: (left) Missions of the Santa Cruz River Valley. Three missions are considered part of Tumacácori Historical National Park. Source: Missions of Tumacácori National Historic Park Overview Draft, South West Learning, National Parks Service (Moss, 1).
Figure 3: (right) Archaeological Map of San José de Tumacácori. Source: Missions of Tumacácori National Historic Park Overview Draft, South West Learning, National Parks Service (Moss, 3).

Built in the early 19th century on Tohono O'odham (Pima)lands, the mission church is a cultural hybrid that embodies the traditions of two cultures. The monument is comprised of remains of the original Jesuit church of the mid-18$^{th}$ century, a new (current) church by the Franciscans in the early 19$^{th}$ century, three *convento* rooms, remains of a buried *convento*, a cemetery, a chapel, a lime kiln, and an orchard and acequia. At one point, the mission contained 5,000 cattle, 2,700 sheep and goats, and 750 horses (Graham 2011, 3).

The mission was established by the Jesuit Father Eusebio Kino who also founded the nearby church of San Xavier del Bac outside Tucson, Arizona. After his death in 1711, most missions were abandoned. The Jesuits were later removed from the Americas in

1767 due to political conflicts that arose between King Charles III and the Jesuit Order. The Jesuits were replaced by the Franciscans who rebuilt larger and often more elaborate and permanent churches. For instance, San Xavier del Bac went from a simple adobe church to the elaborate place of worship it is today (See Figure 4).

Figure 4 San Xavier del Bac, also located in Tucson, is an example of the elaborate churches reconstructed by the Franciscans. Source: *On the Road Again For You* tours, http://www.ontheroadagainforyou.com/san-xavier-mission-del-bac-corona-de-guevavi-tubac/.

Animosity between the O'odham (Pima) Indians and the Spanish led to several revolts in the 18$^{th}$ century, which explains why the Tumacacori mission was relocated to the west side of the Santa Cruz River Valley (Moss, 2). As a result, the mission was renamed San José de Tumacácori. A new church was eventually built by the Pima and Papago Indians under the Franciscan friars, but funds were lacking to complete the construction in a timely manner. After Mexico gained its independence from Spain in 1821, the missionaries began abandoning the area partly due to Apache raids (Graham

2011, 3). Eventually, the few remaining residents left in 1848. For these reasons, the mission remained unfinished and preservation efforts have procured to maintain Tumacácori as a partially restored ruin.

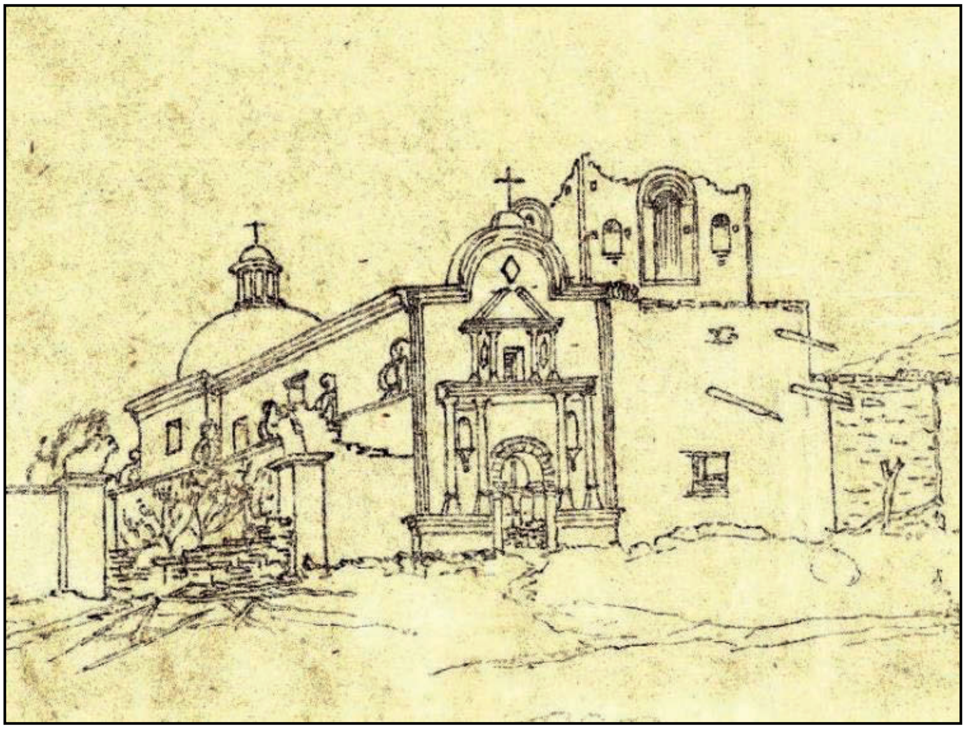


Figure 5: Tumacácori Sketch circa 1849.
Source: H.M.T. Powell. “Tumacácori: HMT Powell sketch ca 1849. Powell drew this sketch in his journal on his way to California.” 1849. *NPS.* https://www.nps.gov/media/photo/gallery.htm?id=FA98A28D-155D-451F-67F12C7DD7B694AE

Figure 6: Tumacácori façade after the 1890 earthquake.[2] Source: Source: Unknown. “In the aftermath of an earthquake in 1890.” NPS. 1912. https://www.nps.gov/media/photo/gallery.htm?id=FA98A28D-155D-451F-67F12C7DD7B694AE

Throughout the years, NPS preservation methods have changed in an effort to preserve the mission complex as a stabilized ruin. It was Frank “Boss” Pinkley, the site’s original superintendent and later administrative leader of the entire Southwest Monuments Group who developed the philosophy of repair and stabilization based on original construction methods and in kind replacement materials. Correspondingly, the

[2] The largest earthquake documented on the southern geological Basin and Range Province, caused irreparable damage to the building’s fabric. The 7.4 magnitude earthquake is said to have caused a large crack in the interior west wall of the mission church, as well as damaging the base of the façade columns and the pediment and choir loft.

intention early on was to restore the mission without the appearance of it looking restored (Attwell and Gordon 1935).[3]

Figure 7: The mission underwent reconstruction and restoration under Pinkley. Source: Unknown. “Tumacácori 1930.” NPS. 1930. https://www.nps.gov/media/photo/gallery.htm?id=FA98A28D-155D-451F-67F12C7DD7B694AE

[3] Afterwards, maintenance of existing conditions became a more popular preservation philosophy depending instead on new chemical treatments, especially for waterproofing.

### 2.1.1 Materials and Construction

The Mission's design and construction embodies Spanish colonial, Mexican, Native American, and Euro-American influences. The Spanish (Jesuits and later Franciscans) introduced the use of lime mortars and sun dried mud bricks or adobes to the native community, while the building's construction and decoration was executed by Native American laborers and artists.

The mission's exterior was originally finished in polychromatic painted lime plaster, with decorative painting in its interior. Fired brick was used for the church façade and unfinished bell tower, laid with lime mortar, while the majority of the structure was built of adobe. The exterior and interior plasters used to finish the adobe and brick surfaces are generally composed of two 1" thick lime plaster layers, followed on the interior only by a thin gypsum wash layer.[4] Described as green while still wet, the surface was hand polished or by using rawhide skin (Jackson to Davis 1948, 2).[5]

---

[4] The walls are mostly composed of adobe bricks with mud mortar beds as thick as the adobe itself, all laid in a traditional manner. However, fired brick is located at the top of the walls, functioning as a cap. The fired bricks were laid with lime mortar.

[5] This was included in a letter written by Tumacácori custodian, Earl Jackson, to Raymond E. Davis, and University of California Division of Civil Engineers on April 13, 1948.

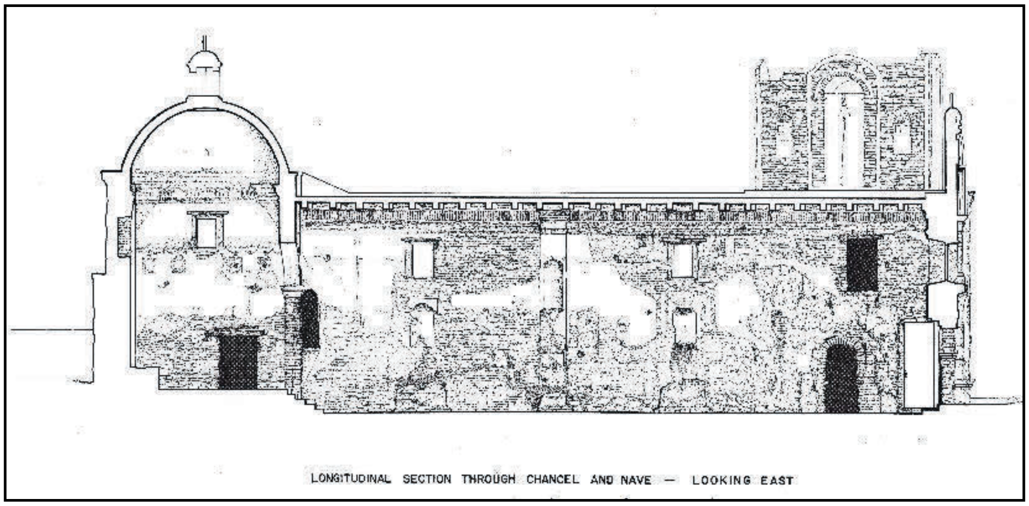



Figure 8: West Wall of Nave section. Source: Longitudinal Section on Line A-A. West Wall of Nave and Sanctuary. Church of San José de Tumacácori. Tumacácori national Monument- Santa Cruz County, Arizona. HABS Drawings. 1975.

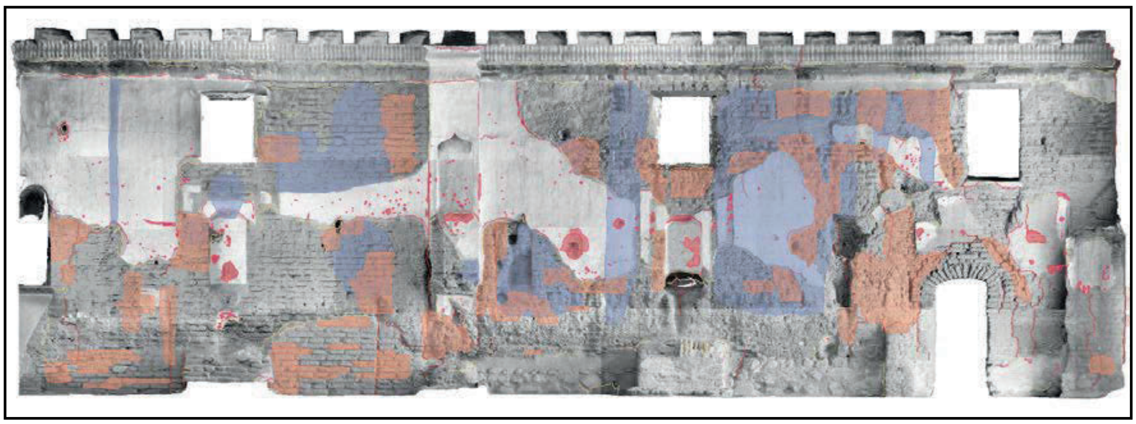


Figure 9: Stitched West Wall of Nave section. Source: Drachman Institute Heritage Conservation. Interior Condition Assessment Report. Tumacácori National Historic Park. College of Architecture, Planning, and Landscape Architecture. The University of Arizona. In conjunction with Desert Southwest Cooperative Ecosystem Studies Unit. July 2006: 72, 76, 80.


Figure 10:  Illustrations of Façade. Source: "Detail of South Facade- San Jose de Tumacacori (Mission, Ruins), Tubac, Santa Cruz County, AZ." 1949. Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA http://hdl.loc.gov/loc.pnp/pp.print


Figure 11: Illustrations of Altar. Source: Trujillo, Jimmy. "Detail of Sanctuary Showing Altar - San Jose de Tumacacori (Mission, Ruins), Tubac, Santa Cruz County, AZ." 1949. Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA http://hdl.loc.gov/loc.pnp/pp.print

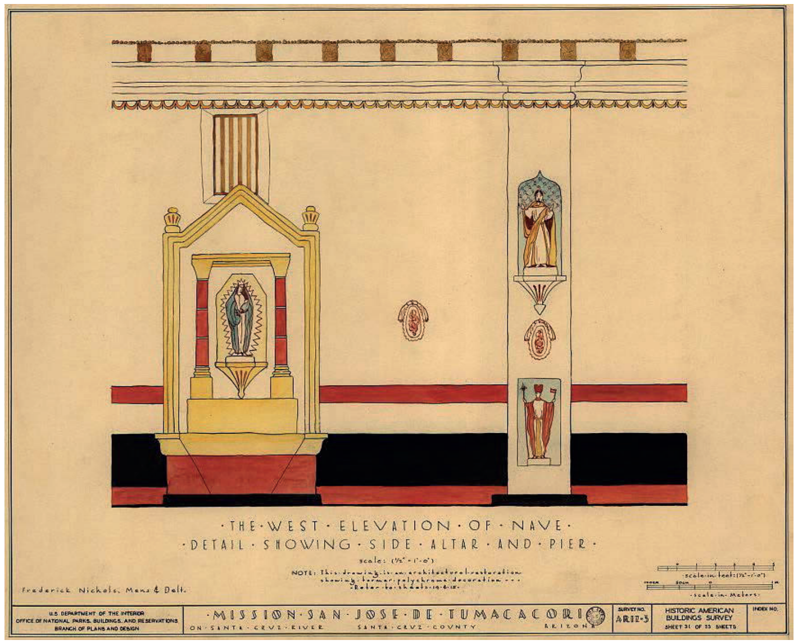



Figure 12 Nave Elevation illustration. Source: "West Elevation of Nave, Detail Showing Altar and Pier- San Jose de Tumacacori (Mission, Ruins), Tubac, Santa Cruz County, AZ." 1949. Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA http://hdl.loc.gov/loc.pnp/pp.print

Most of the materials employed for its construction were locally sourced or made on site (Steen and Gettens 1949, 10). The lime used for the plaster was probably made in the lime kiln located a hundred yards north of the building. Historical documents describe the plaster as mostly made of lime putty with sand tempering (Jackson 1948). Historic accounts obtained from Raymond E. Davis, claim the lime was made by burning impure limestone from deposits found in nearby hills.[6] Davis also speculated that the plaster was made from a weak hydraulic lime or cement (Davis 1948); however, no pozzolanic compounds have been identified during more recent analysis.

[6] The Roman custom, volcanic ash and sand containing volcanic glasses, was also speculated to have been used for the plaster mix.

The dome was built using similar sized fired bricks to provide more stability. The dome's interior was coated with two plaster coats followed by a gypsum wash. The exterior was covered by lime plaster, and later, cement stucco (Mulhern 1985).[7]

The foundation was made out of cobblestones from the river bed located less than half a mile away. The floor was made with broken brick laid with lime mortar covered with a red painted plaster wash (Steen and Gettens 1949, 11).

### 2.1.2 Plaster Composition & Description- Previous Analysis

Plaster samples were first analyzed by Earl Jackson in 1948. Results confirmed the binder was composed of slaked lime, which had completely carbonated. There was no evidence of any hydraulic compounds (Davis 1948).[8] The quicklime used for the plaster contained 92% calcium carbonate, and 4 % iron oxides and aluminum. The plaster analysis estimated the original proportions of the mix to be: 1 part lime putty to 3.5 parts bank sand. No evidence of organic fibers was found in the plaster. The sand's fineness modulus was around 2.1 (Davis 1948). According to Steen and Gettens (1949), the plaster was estimated to contain 20-25% lime and the finish coat was:

> …mainly burned gypsum, which has reverted back to the dihydrate, CaSO4.2H20. (…)in addition to the fine crystalline calcium sulphate dihydrate which makes up the bulk of the white finish coat, there is a fair amount of coarser fibrous crystalline material not ordinarily found in gypsum plaster. (...)The gypsum layer is only 1-2mm thick and was probably applied as a water paint or whitewash. (Steen and Gettens 1949, 35).

---

[7] This is part of a memorandum prepared by Tom Mulhern in May 31, 1985.

[8] Hydraulic compounds, or a substance that might have been used as a hardener nor any calcium silicate formation, which could have stemmed from lime and reactive silica formation.

More recent petrographic analysis of the exterior plaster was performed by *Highbridge Materials Consulting* in 2014. The sample was retrieved from the sacristy roof, and was identified as a "high-calcium lime mixture containing a well-graded, natural sand. No hydraulic or pozzolanic material was detected…" (Highbridge Materials Consulting, Inc. 2014). The report also noted the original materials were well mixed and well consolidated. The amount of sand in the mix was significant, doubling the putty lime used. Overall, the plaster was a light gray color and its binder was soft and permeable, yet cohesive.

### 2.1.3 Adobe Composition & Description

The adobe was characterized during the 1970s. In 1976, Charles E. O'Bannon was consulted to find a treatment to strengthen the adobe against erosion, with a particular focus on electro-chemical treatment.[9] To assess how feasible this irreversible treatment was, two sites were selected: Casa Grande National Monument and Tumacacori National Monument. O'Bannon realized most of the preservation efforts throughout the years focused on plaster characterization.

Soil near the site was analyzed by O'Bannon due to the likelihood that this was the same soil used for the adobe construction. The soil was described as well graded, containing 66% sand and 34% silt and clay.

> …medium gray when dry, dark gray when wet, inorganic, fine grained, sandy silty clay with low plasticity and dry strength, classified as CL under

[9] Chemical solutions applied to the material goes into the pores, and attempts to replace weaker bonding ions in the soil with stronger ones, with the purpose of increasing strength properties. Such treatment is irreversible (O'Bannon 1978).

> the unified soil classification system. The index properties are as follows: 1) Specific gravity: 2.55, 2) Plasticity index: 6 (O'Bannon 1978, 13-15).

His overall conclusion found the soil to be a weak construction material. Paul Graham McHenry also analyzed the soil composition used for the adobes at Tumacacori, and found a larger amount of sand and silt (McHenry 1989, 50).

TABLE 3.1
**Soil Material Composition for Adobes, Mortar, and Mud Plaster—Average Percent of Total Sample**

| Location | Gravel | C Sand | F Sand | Silt | Clay | Porosity |
|---|---|---|---|---|---|---|
| Tumacacori, Arizona[a] | | | | | | |
| Adobes | | | | | | |
| P1 10 samples | 14.4 | 20.2 | 24.8 | 27.8 | 13.9 | 32.3 |
| P2 8 samples | 10.7 | 23.7 | 30.1 | 25.8 | 9.7 | 33.1 |
| P3 12 samples | 10.5 | 22.2 | 28.9 | 27.0 | 11.2 | 34.6 |
| P4 8 samples | 12.1 | 24.4 | 29.8 | 24.9 | 9.0 | 31.0 |
| P5 13 samples | 8.0 | 18.6 | 30.1 | 26.7 | 18.0 | 34.2 |
| P6 10 samples | 8.2 | 19.7 | 29.4 | 31.1 | 11.5 | — |

Figure 13 Tumacácori Soil Composition. Source: McHenry, Paul Graham. Adobe and Rammed Earth Buildings: Design and Construction. University of Arizona Press, 1989.

Additional characterization of adobe specimens was performed in December 1976 by Micromeritics Instrument Corporation, Paul W. Brown, Carl R. Robbins and James R. Clifton to analyze pore structure, particle size distribution, density, and mineralogic and petrographic characterization. Some of the specimens sampled were poor in clay size material, moist and poorly consolidated (Robbins 1976; Brown et al. 1979). The overall color was dark brown, Munsell color 7.5 yr 4/2, and the adobe contained many fine pores. Gypsum particles measuring up to 0.5mm were found, as well as carbonates, perhaps calcite.

> Tumacacori adobe indicated that the sand was subjected to abrasive action. Particles of this size tend to become rounded through the action of running water. This suggest that the soil or sand was obtained from a stream near the site (Brown et al. 1979, 31).

Adobe specimens collected for consolidation contained the following minerals: quartz, rounded fragments of quartzite, euhedral crystals of unaltered alkaline feldspar, angular to rounded grains of calcic feldspars, muscovite, altered amphibole, biotite mica, ilite, gypsum, rutile, titanite, hematite, kaolinite clay (Brown et al. 1979, 30).

> The silt and the fine quartz sand fraction is quite angular and forms interlocking particles in the clay-silt matrix, In the coarse fraction (aggregate) the quartz is subangular to rounded. Alkaline and calcic feldspars were observed in both the aggregate and finer fractions (Robbins 1976, 2).

In other specimens the feldspar was heavily altered to illite and kaolinite clays. A characteristic feature of this adobe shows most of its feldspar has chemically altered to clay. Organic matter, such as straw preserved in the finer fractions was found in all the adobe specimens. Only one of the soil specimens contained expansive or swelling clays, however there was no evidence of expansion cracks on the adobe specimens (Robbins 1976, 3). X-ray diffraction identified montmorillonite clays present. The team also found traces of calcium, sulfur, potassium, and chlorine (Brown et al. 1979, 34).[10]

[10] The diffraction pattern of a small fraction of one of the soil samples was that of 14.7 Å. Some of the specimens expanded to 17 Å with glycolation.

Overall, the samples from Tumacácori contained a large amount of silt and clay, but the team suggested coarser fractions might have been added to achieve the desired proportion (Brown et al. 1979, 35). It was ultimately concluded that the presence of soluble salts found in the samples was due to rising ground water. The mix used to build the adobe for the church appeared to be composed of one part soil with four parts sand (Brown et al. 1979, 38). Mineralogical analysis also indicated the deterioration in the samples was not due to the presence of swelling clays.

Adobe samples were also analyzed in 1978 as requested by George Chambers using a variety of tests, such as x-ray diffraction of the clays. Overall, the clay fraction was low when compared to the sand and silt fractions, and the plasticity index was 5, indicative of low shrink-swell potential. According to Chambers, "(…) the soil should be acceptable as an unamended mud plaster (or mortar) but it would be advisable, if possible, to make a test application before acquisition" (Physical Science Technician 1978, 7).

TABLE 8

DENSITIES AND POROSITIES OF SELECTED ADOBE SAMPLES

| *Sample designation* | *Density g/cc* | *Net pore volume cc/g* | *Average pore diameter* $\mu$m | *Measured total porosity** % |
|---|---|---|---|---|
| To10 | 2·56 | 0·233 | 4·2 | 37·4 |
| To11 | 2·56 | 0·213 | 14·0 | 34·5 |
| To12 | 2·60 | 0·199 | 2·5 | 33·9 |
| To17 | 2·46 | 0·318 | 4·8 | 43·0 |
| Fort Bowie | 2·68 | 0·150 | 3·4 | 27·9 |
| Escalante | 2·80 | 0·227 | 2·8 | 38·2 |

Figure 14 Density of Tumacácori adobe samples. Source: Brown, Paul Wencil, Carl R. Robbins, and James R. Clifton. "Adobe. II: Factors Affecting the Durability of Adobe Structures." *Studies in Conservation* 24, no. 1 (1979): 35.

These analyses confirm the probable source of the adobes as local soils given the geological context of Tumacacori.[11] The Santa Cruz River valley contains a considerable amount of alluvium, “which generally has a high permeability typical of sand and gravel deposits but which locally may be characterized by a predominance of fine sands and silts” (Percious 1978, 3).

**2.2 Conditions and Factors Enabling Deterioration**

The mission buildings sit atop a natural drainage system that travels from the Tumacácori Mountains to the Santa Cruz River (Moss 2008, 12). As a result, a vast quantity of soil moisture collects without any space to evaporate and the moisture is wicked up through the wall through rising damp.[12]

The largest earthquake documented on the southern geological Basin and Range Province in 1890 caused irreparable damage to the building’s fabric. The 7.4 magnitude earthquake is said to have caused a large crack in the interior west wall of the mission church, as well as damaging the base of the façade columns and the pediment and choir loft (Moss 2008, 5). The nave roof collapsed a few years after it was fully abandoned in 1848, exposing the interior to outside elements; however the Sanctuary dome and

---

[11] A rotary drilling rig was used to dig twelve holes around the mission in 1970 with the purpose of determining the source of moisture causing rising damp in the nave and sacristy walls: “two distinct strata noted: the first at one foot below present ground surface (…). The top was a dark gray stratum; the bottom contained a zone of lime plaster fragment with fine, burnt clay fragments throughout. Damp soil extends about two feet lower than in Hole #1” (Richert memo 1970, 2).

[12] In the early 1950s, draining issues were repaired to some extent which reduced run-off and flooding, but overall subsurface water still continued to travel up the mission's west wall. By 1955 it was reported that the repair was apparently successful since there were no leaks in the roof or walls during Arizona’s rainy season (Ringenbach 1955).

Sacristy barrel vault remained intact. The nave roof was later rebuilt in 1921 during Pinkley's stabilization efforts. In addition to seismic damage and exposure to weather for a significant number of years, vandalism has caused considerable damage.[13]

As early as the 1940s, the interior plaster had been found to be friable, quickly powdering, resulting in loss of plaster and painted decoration. Most of the plaster on the lower walls has been lost, presumably from rising damp and vandalism. The uppermost walls have also lost plaster as well as their original brick coping due to roof collapse. The plaster that remains to date, despite earlier preservation efforts, is largely detached from its adobe substrate in many areas, producing hollow sounds when tapped. Aside from this detachment, animal activity, mainly that of bats and birds, inside the building, has exacerbated conditions, causing plaster discoloration and in some instances, nesting had caused plaster fragments to fall (Clemensen 1977, 69; Steen and Gettens 1949).

By 1935, the church was reported as "unfloored" and dusty to which Engineer Gordon recommended flooring the nave using red colored cement to recreate the original red plaster floor (Woodward 1935, 3). For the most part, the walls and floors varied in their state of preservation. Some of the floors had a plaster finishg while others remained as packed adobe.

It is reported that from 1936 to 1939, both the interior and exterior conditions of the church worsened as indicated by severely detached and large missing areas of plaster

---

[13] Swarms of treasure hunters tore walls and floors searching for hidden gold and jewels for more than 70 years. In addition to treasure hunters, other visitors would collect painted plaster as souvenirs, as well as inscribe their names on the plaster, which is documented today as graffiti.

due to the weather and the visiting public (NA- Report on Current Conditions of Each Historical Structure 1941, 1). Detachment of the interior lime plaster from the adobe was also due to poor bonding between both materials from the start. The exterior lime plaster has weathered differently due to varying exposure and inconsistency in the plaster composition and its subsequent repairs (Jackson to Gettens 1949).[14]

Water seeping through exterior cracks was another avenue allowing water to enter the interior. By 1946, it was reported the exterior plaster had continued to decay, particularly on the west and the north walls (Clemensen 1977, 72).[15] Torrential storms in the summer of 1944 worsened conditions even more, when a portion of the remaining pilaster fell, painted plaster peeled from the capitals, and cracks continued expanding through the moldings and windows (Steen 1946, 2).[16] A large exterior crack, measuring 12 feet long by ¾ inches wide, developed at the north end of the nave due to roof flashing failure.[17] This allowed heavy rains to access the crack and fill the arch beneath with water (Jackson 1946, 1).[18]

---

[14] The Superintended, Earl Jackson, sent fallen samples from both the exterior and interior plaster to Gettens. The sample of exterior plaster had previously fallen and retained a dark pigment, indicative of a decorative band. The interior plaster was much smaller in size, and Jackson indicated there were two layers, "…the last of which covered an older layer of bluish pigment. I presume this bluish pigment is typical of other bluish pigment which forms part of the existing surface decoration in the sanctuary" (Jackson to Gettens, 1949). This was included within a letter.

[15] It was reported that Charlie Steen found the mission in "disturbing condition" after his February 1946 visit (Clemensen 1977, 72)

[16] This was included in a memorandum prepared by Steen for the Associate Regional Director in March 5, 1946.

[17] The crack was filled by Jackson with cement and gravel (Jackson 1946, 1).

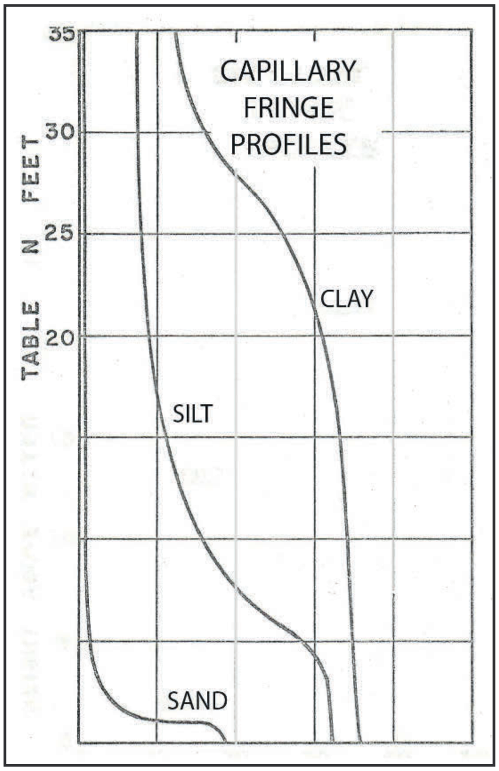
[18] This was included in a memorandum prepared by Earl Jackson, custodian, for the Regional Director Region Three, May 25, 1946.

Rutherford J. Gettens and Charlie Steen arrived at Tumacácori in 1949 to carefully analyze the finishes. They found the interior plaster to be flaking, particularly in the sanctuary dome. As part of a routine maintenance checkup in April of 1950, Jackson noted most of the original plaster had continued to weaken and fall. Two months later one square foot of plaster fell from the interior Sacristy wall (Clemensen 1977, 30). Jackson linked the recurring events to a roof leak, which he later sealed with a sand, lime, cement mortar. Between 1952 and 1953, heavy rains caused one square foot of the red painted plaster to fall, as well as a significant portion of the original plaster on the cemetery's east side (Clemensen 1977, 79).

The entire roof system was failing by 1974, and so it was recommended to remove the roofing and sheathing while still retaining the existing beams. Due to termite infestation, it was recommended the beams be termite-proofed (Herreras 1974).

Previous investigations by D. D. Evans in the 1970s concluded that the moisture gradient in the church's southwest corner was 3.4% near at the inside surface, 20.4% at a depth of 18 inches, and finally lowered to 15.4% at 28 inches (Percious 1978, 12). Chemical salt testing performed in 1977 also concluded soluble salts and calcium concentration was fairly high. Efflorescence on the plaster was causing the paint to peel from the wall (Yancey to Cattanach 1979).[19] The ground water table was found to be at 25 feet (Percious 1978, 27).

[19] This was included in a letter written by structural engineer, Charles Yancey, to George S. Cattanach, Chief of Division of Adobe and Stone Conservation on July 24, 1979.



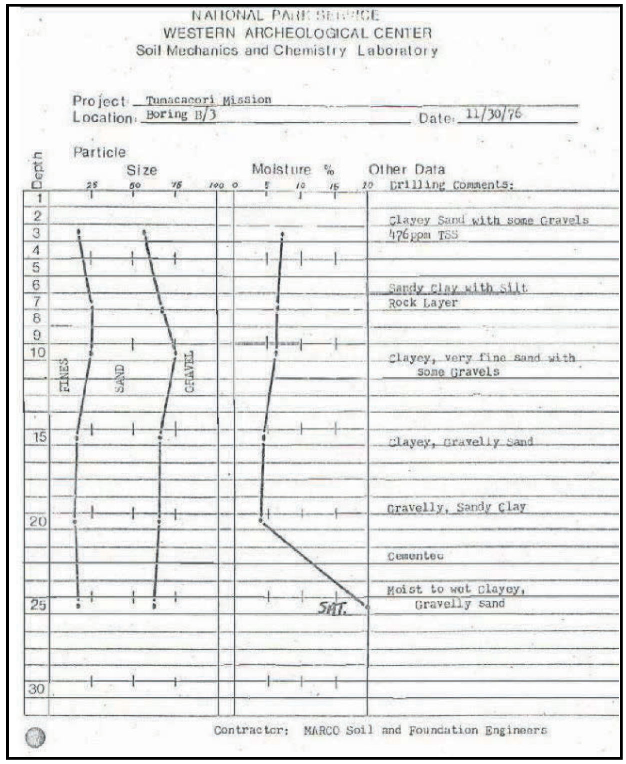




Figure 16 Tumacácori Fringe Profile. Source: Percious, D.J. and M. Norvelle. Report on the Examination of Available Evidence on the Deterioration of the Walls of the Tumacacori Mission. Tucson, AZ: University of Arizona, 1978, 53.

Figure 15 Data collected on Boring B/3 by Marco Soil and Foundation Engineers. Source: Percious, D.J. and M. Norvelle. Report on the Examination of Available Evidence on the Deterioration of the Walls of the Tumacacori Mission. Tucson, AZ: University of Arizona, 1978, 64.

The moisture content at the pendentives was close to 10%. This reinforced the hypothesis the water was filtering from above the dome and roof and was migrating to both the exterior and interior surfaces of the dome, pendentives and wall (Yancey to Cattanach 1979). By January of 1977, there was additional loss of 5% painted plaster in the Sanctuary. By March of 1977, the plaster loss had extended to 35% (Davis to Hall, 1977, 1).[20]

[20] This was included in a letter written by John H. Davis to Dorothy Hall, State Historic Preservation Officer on March 25, 1977.

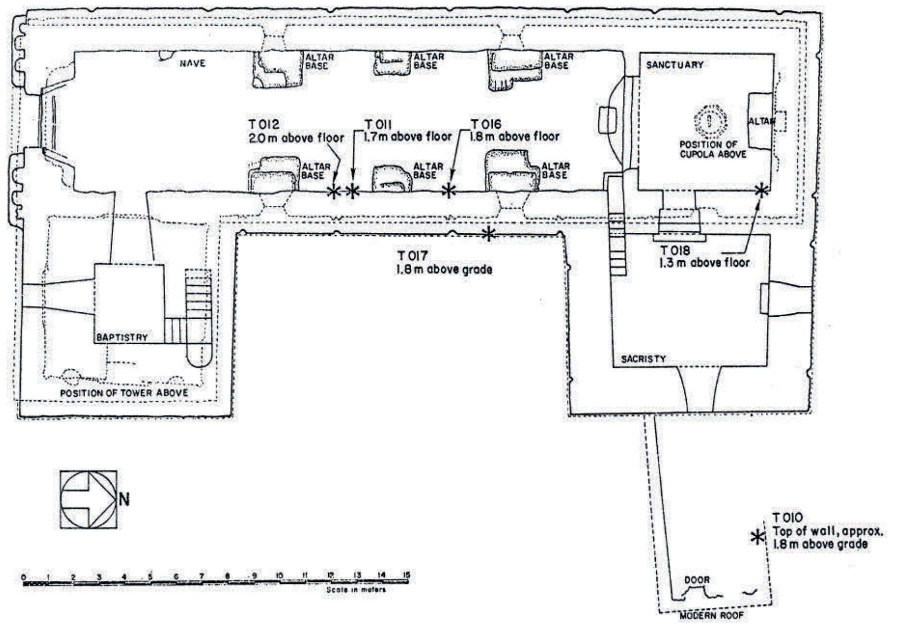



FIG. 5 A scale drawing of Tumacacori National Monument showing the sampling locations.

*Studies in Conservation*, 24 (1979), 23–39

Figure 17 Sample Locator Map. Source: Brown, Paul Wencil, Carl R. Robbins, and James R. Clifton. "Adobe. II: Factors Affecting the Durability of Adobe Structures." Studies in Conservation 24, no. 1 (1979): 29.

Analysis and recommendations regarding moisture penetration were made on November 1976 by Dr. James Clifton and Erik Anderson of the National Bureau of Standards. The ideal moisture content for the adobe was calculated to be 1 - 3% (Clifton to Cattanach 1976, 2).[21] Moisture measurements made by Anthony Crosby in 1985 showed the adobe at Tumacácori exceeded the optimum moisture content. All reiterated that the sources of the excess moisture in the mission were the ground water table located 25 feet deep with a pressure head of 5 feet, rain penetrating the exterior cement repair plaster, and rain entering the roof (Clifton to Cattanach 1976, 3).

[21] This was included in a letter written by James Clifton to George Cattanach of Western Archeological Center on December 3, 1976. This letter includes a report prepared by Clifton.

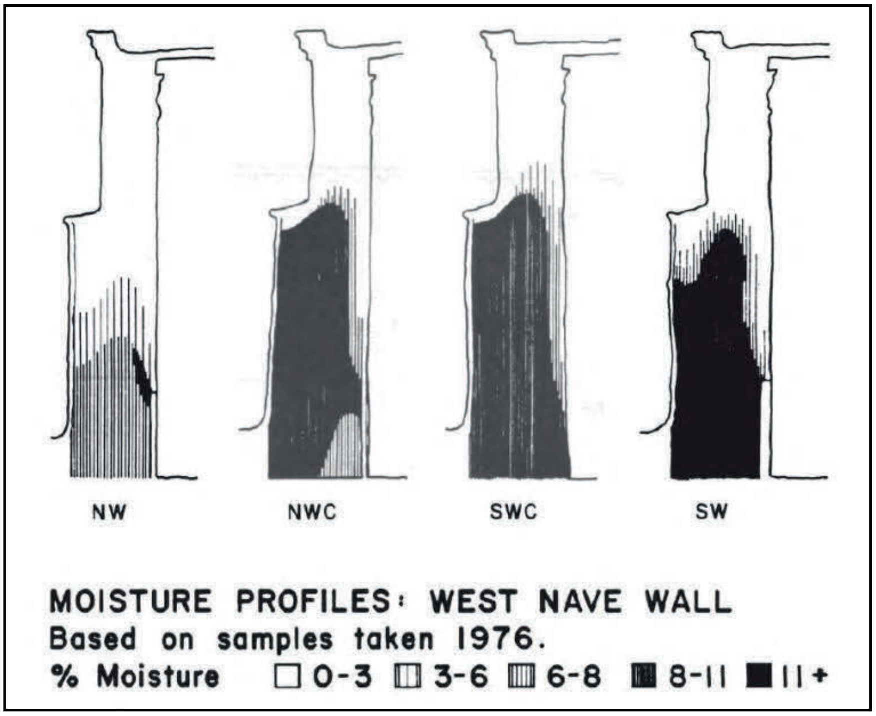


Figure 18: Moisture Profiles of the West Nave Wall. Source: Crosby, Anthony. Historic Structure Report: Tumacacori National Monument Arizona, 1985: 105.

## 2.3 Conservation Treatment History at Tumacácori

As was common in many past preservation and restoration treatments of historic buildings, artificial or Portland cement became the preferred repair material, especially after the 1940s, and remained popular for decades. Waterproofing compounds as well as cementitious coatings exacerbated conditions. Because Portland cement is more

**1889:** Missing roof at the nave looking toward the sanctuary of the Tumacácori Mission.

Figure 19: Roskruge, George. *Nave of Tumacacori Mission looking toward choir loft and entrance.* 1889. Classification No: 266.2791, Negative No. 1060, U.S Department of the Interior, NPS, Coolidge, Arizona.

**1919:** Before construction of new roof and before the pulpit was restored and plastered. A large area of plaster on the walls is missing. Floor cleared.

Figure 20 Collier, Marguerite L. *Church interior, nave, looking toward sanctuary.* 1919. Classification No: File 502. U.S. Department of the Interior, NPS, Coolidge, Arizona.

**1945:** Roof has been in place for around 25 years, floor has been restored as well.

Figure 21: Reed, Harry. *Interior of Tumacácori Mission Altar View. 1945*. Classification No: 266.2791. Negative No. 1/470, 915. U.S. Department of the Interior, NPS, Coolidge, Arizona.

impermeable than lime plaster or adobe, it traps and diverts moisture, causing erosion beneath the plaster and around the edges of cement repairs. It also causes disintegration of original adobe. Inserting metal mesh with layers of cement was also a popular treatment solution to hold the lime plaster on exposed areas throughout the 1920s and 1940s.[22]

### 2.3.1 Conservation Treatments: 1920s to 1960s

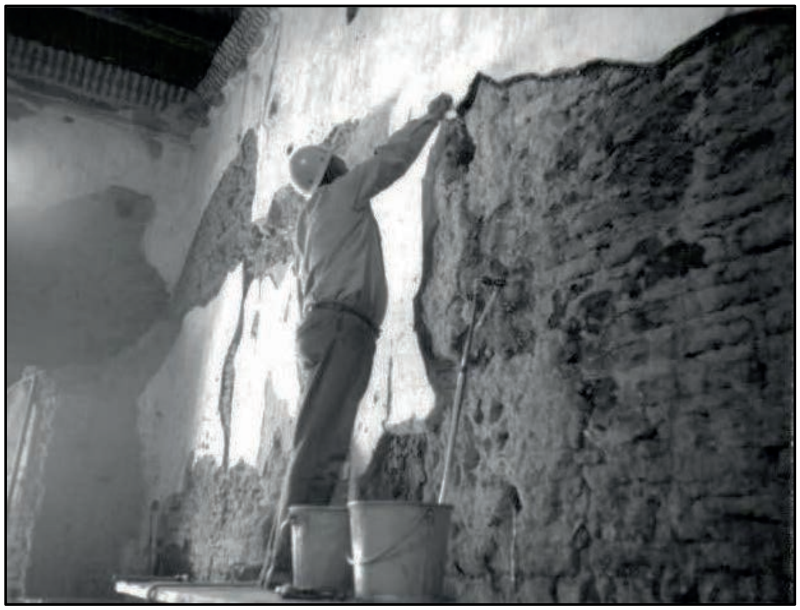


Figure 22: Grouting white cement to lower edge of plaster. Source: Henderson, Sam R. Stabilization Report: Tumacacori National Monument 1972. Arizona Archaeological Center, Ruins Stabilization Unit: Tucson, AZ, 1972: 42.

The Mission's first major stabilization efforts were undertaken by Frank Pinkley during the 1920s (Caywood 1944). The work included rebuilding the pediment near the choir loft window, extensive re-plastering of the exterior north end of the building, and replacement of the missing nave roof (Clemensen 1977). As other conditions worsened due to exposure to the elements, The Civil Works Administration workmen repaired walls with missing plaster in 1934 by affixing a one-inch mesh, eighteen-gauge netting onto the wall using three-inch box nails (Clemensen 1977, 68). The mesh was then covered with a

[22] Metal lash application mostly done by Earl Jackson following King's work.

cement mix of one part cement to four parts sand, and a final coating of lime plaster. Strips of metal lath plastered over exposed adobe was later applied in 1947 (Clemensen 1977, 75).

Initial treatments to deteriorating adobe in 1935 consisted of applying a 3% solution of NPSX, a custom formulated vinyl resin solution in acetone and toluene made for the National Park Service (Crosby 1985, 12). Two coats were sprayed with compressed air at 60 lbs pressure on the east side (exterior) of the south entrance, and on the Nave's interior, mostly spraying exposed adobe and colored plaster (Clemensen 1977, 69). Other recommendations for the decaying adobe was to nail tar paper to the frames, and later apply linseed oil to the canvas frame (Richey 1941, 1-2).

One inch wide cracks were commonly found along the Sacristy barrel vault, the roof gutters and downspouts. On July 9, 1941, the cracks were initially cleaned, widened and sealed by Louis Caywood, with a soluble black mastic solution that worked as a waterproofing coating. The mastic solution entered the moist cracks to form a tight bond with the lime plaster. Sand was used as an infill to account for shrinkage (Caywood, 1941).[23] Oakum was also used along with mastic as a temporary solution to seal the top area of the cracks to prevent water penetration that was causing original plaster to detach. The treatment was later deemed satisfactory (Richey 1941).

[23] This was included in a memorandum prepared by Louis R. Caywood, custodian, for the Superintendent of the Southwestern National Monuments on July 11, 1941.

Three years later, cracks located on unplastered sections of the bell tower's north wall and east side of the mission were grouted with either a mixture of Stabinol®, a proprietary asphalt emulsion stabilizer for adobe and clay roadbeds, and fortified soil or cement plaster (Clemensen 1977, 71).[24] The formulation for the Stabinol® solution consisted of 6 shovels of screened soil and 1.5 shovels of Stabinol (Richey 1941, 1).

Structural mortar formulations in 1946 consisted of 3 parts sand: 1 part cement: 1/3 part lime putty (soaked hydrated lime). The partially hydrated putty was slaked a day before application. Cement used to fill holes consisted of 3 parts sand: 1 part lime (Jackson 1951, 2).[25] Cement to cover surface cracks and losses in the original lime plaster were patched with a formulation of 3 parts sand: ¾ parts hydrated lime, and ¼ part cement. The mix was applied using a pointing trowel while carefully pressing the mortar into the cracks. Once the plaster became dry, it was painted with a mixed paste consisting of 3 oz. burnt umber, 6 oz. yellow ochre and water which was added to 3 lbs. of processed lime putty, and further mixed with 2 gallons of water. Afterwards, the surface was washed with mud water and a tinge of red clay (Lancaster 1947, 1-2).[26]

To stabilize the interior and exterior plaster, the lime mortar or cement mix was keyed properly unto the adobe. Grouting material often flowed into cracks and voids to achieve

---

[24] Stabinol was commonly used in the mid-1940s for soil stabilization. This chemical method was typically used to make soil waterproof.

[25] This was included in a memorandum prepared by Earl Jackson, Tumacácori Superintendent, for the General Superintendent of the Southwestern National Monuments on July 31, 1951.

[26] This was included in a memorandum prepared by James A. Lancaster, Archaeologist Aide, for the Regional Director Region Three on July 31, 1947.

proper binding. The weight of the grout or cement used was supposed to fall mostly on the adobe, not the plaster (Steen and Gettens 1949).

Regarding the interior painted decorations, the term “fresco” was deemed inappropriate as the decoration was originally applied to the dry plaster, also known as “secco”. At one point, an employee sought to clean dirt of the painted decorations and the pigment was inadvertently removed. This led Earl Jackson to believe that the paint was applied to a dried surface and that the colors were mineral and not vegetable (Jackson 1948, 2).[27]

In 1947, the west exterior façade was patched with two coats of Horn Duocrex®, a weather resistant sealant (1947 Jackson memo, 1).[28] [29]Duocrex was again used in 1958 to treat the fired adobe floors that were wearing due to visitor traffic. In 1948, heavy scratch coats of lime plaster were applied to the interior walls at ¾” thick. The finish coat was half the thickness of the scratch coat and was lightly floated to give the appearance of a thin layer of pure lime (Jackson 1948, 3).[30] Spackling paste, a gypsum plaster and glue putty, was used to patch interior cracks in 1949. Metal lath strips were once again nailed to the interior wall and plastered (Steen and Gettens 1949, 48).

---

[27] This was included in a memorandum prepared by Earl Jackson, Tumacácori Custodian, for the Regional Director Region Three on February 5, 1948. Subsequent analysis has confirmed the painting is indeed secco work.

[28] This was included in a memorandum prepared by Earl Jackson, Tumacácori Custodian, for the Regional Director Region Three on September 26, 1947.

[29] Duocrex®, sold by the A.C.Horn Company at the time, was used as a sealant to make floors damage resistant.

[30] This was included in a memorandum prepared by Earl Jackson, Tumacácori Custodian, for the Regional Director Region Three on February 5, 1948.

Gettens formulated a polyvinyl acetate (PVA) lacquer solution, which was sprayed over the interior walls after thoroughly cleaning the plaster surfaces. A thinner coating was sprayed afterwards to facilitate the penetration of the lacquer into the plaster and to diminish any glossy appearance (Steen and Gettens 1949). Getten's formula consisted of:

> Vinylite A, medium viscosity (PVA), 50 grams was mixed into solvent mixture of toluene 700ml, ethylene dichloride 200 ml, cellosolve (trade name for ethylene glycol monoethylether) 40 ml, cellosolve acetate 40 ml, cellosolve acetate 40 ml, and dibutylphthalate 2ml (Steen and Gettens 1949, 25).

The substance was used to keep plaster from chalking and to preserve the colors on the lime plaster. By 1950, the PVA treatment had been sprayed on the interior surface of the Sanctuary, Nave and Baptistry.

In 1951, Jackson introduced Dehydratine Number 2A®, a colorless kerosene-based wax substance, from the A. C. Horn Company, to treat the original exterior plaster, but the treatment proved unsuccessful (Clemensen 1977, 76). Dehydratine 22 was later considered to seal the interior floors (Rigenbach 1958, 1).[31] Jackson's scratch coat and finish coat formulation was later used in April 1952 to reconstruct the plaster on the Mission's west exterior wall (Clemensen 1977, 76). The scratch coat was applied over galvanized metal lath.

Other usual repairs for loose plaster consisted of securing the edge of the interior plaster with nails and covering with plaster. In addition to the walls, this treatment was

31 This was included in a letter prepared by Ray Rigenbach to the Superintendent of the Fort Union National Monument on April 1958.

also applied on the vault. The overall thickness remained at 2” and the surface remained wet for two days. Soon after in March 1959, Joel Shiner was tasked to repair the mission’s vaulted Sacristy roof. The treatment consisted of removing and replacing the plaster with a cement, perlite, lime and sand formulation. Metal lath strips were nailed to the roof before application. Once finished, the roof was covered with two coats of “latex paint and silicone.” Shiner also mended eroded plaster edges with Rock Hard Putty® (Clemensen 1977, 80).[32] [33]

Figure 23: A worker tapping a pin into the previously bored hole. The inserted pins were later grouted over. Source: Sudderth, W.W. The Nave and Bell Tower Stabilization Report 1973. Tumacacori National Monument. Ruins Stabilization Unit. Arizona Archaeological Center. Tucson, Arizona, 1974: 48.

[32] Joel Shiner mainly patched the entrance arch with Rock Hard Putty. He also placed a large patch on the baptistery window sill.

[33] Rock Hard Putty has been on the market for more than 80 years. It's composed of Plaster of Paris, talc, dextrin, crystalline silica-quartz, and yellow iron oxide.

### 2.3.2 Conservation Treatments: 1970s

Mission San José de Tumacácori's foundations were exposed near the nave walls in August 1970. After replastering the foundation, an elastomeric membrane called Thiokol® was applied to the dry surface to function as a moisture barrier. A twenty millimeter thick polychloride vinyl liner was later adhered to both the east and west nave foundation. The apron was buried 15 feet from the mission (Clemesen 1977, 83). The vinyl apron was later removed in the summer of 1977 (Percious 1978, 2).

In 1972, the nave exterior was covered with a tinted wash and bonding agent solution composed of cement, mortar color, and Daraweld® plaster adhesive to eliminate the uneven "polka dot" wall appearance (Henderson 1972, 7).

Building inspections in the 1970s estimated that approximately 60%-75% of the interior and exterior plaster was not bonded to the adobe substrate (Herreras 1974, 3). The plaster was described as hollow and unsafe. Cement grouting with wire mesh strips to reattach the plaster to the substrate was performed on the interior walls of the nave. The 1970s also included the use of F-325 repellent and sealer® and epoxy grouting techniques, an irreversible method, to treat the plaster (Herreras 1974, 32).[34] Exterior repair plaster was made of lime-cement mortar while the interior plaster used lime mortar, and had a sand finish.

Major preservation efforts began in 1976 and carried through until 1982. In 1977, the NPS hired the Office of Arid Lands Studies (OALS) to investigate the mission's

34 F 325 acrylic used to treat adobe with sealing compounds was known to change the color of the adobe. Such is the case of the observation building at Ft. Bowie (Herreras 1974, 32).

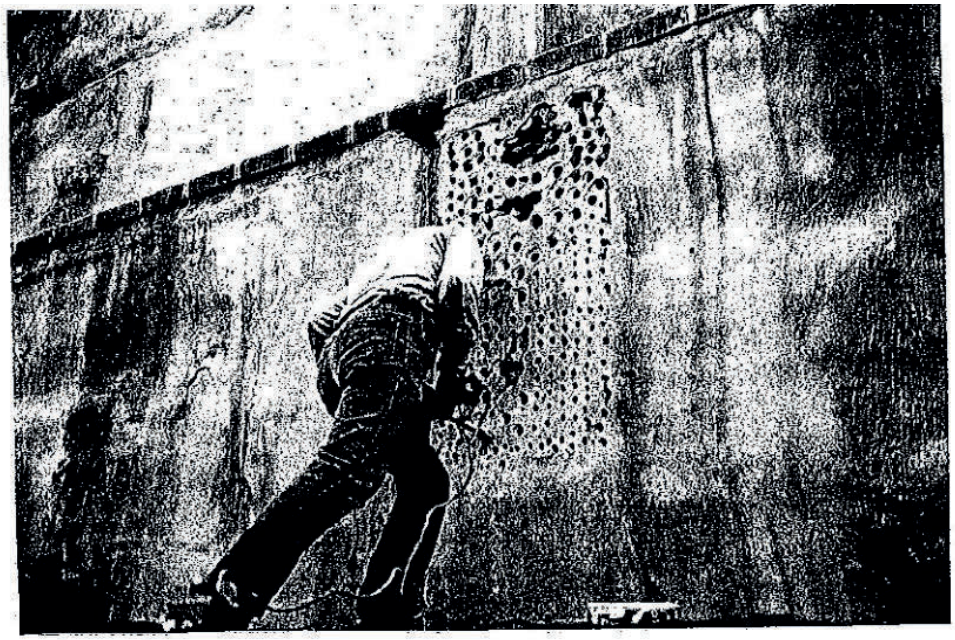
deteriorating wall condition, the source of wetting, and efflorescence. This was investigated through soil borings conducted by Marco Soil and Foundation Engineers, Inc. The base of the walls, particularly the southwest corner, appeared to be receiving the most moisture, which was identified as coming from the underlying soil. The roof and scuppers (canales had been repaired) and a vinyl apron had been installed at the base of the wall to channel drainage water.

Throughout testing the source of the moisture remained inconclusive, however the soil was further characterized. The report ruled that the water table was far too deep for capillary rise to occur at a significant level.

> Particle-size distribution for all borings indicate poorly sorted and heterogeneous soils for the soil columns sampled by the borings; thus, the soil can be characterized as being dominated by fine-grained particle sizes (Percious 1978, 1).

The team also found that “the presence of a retarding layer, not greater than 10 feet deep” may be a factor contributing to a “soil moisture reservoir” (Percious 1978, 1).

Recommended treatments included sealing the adobe foundations and installing a rain gutter system to minimize a soil moisture reservoir close to the mission’s foundations (Percious 1978, 33). The report also warned against using cement plaster as it is not as breathable as the adobe substrate. (Percious 1978, 3). It was later recommended that the Portland cement plaster repairs should be removed during the dry season and replaced with an adobe plaster. The cement was working as a vapor barrier trapping in moisture.



In addition to drilling holes through the cement plaster to determine its depth, holes were also drilled near the south end of the west nave wall to hasten drying of the moist adobe walls.

Figure 24: Holes drilled through cement plaster. Source: Chambers, George J. Tumacacori Preservation Project: Field Activities 1977, 1978, and 1979. Western Archeological Center, 1981, 13.

Prior to removal of the cement plaster, test holes were drilled into the exterior cement plaster to determine the depth of the patchwork. During the removal process, the team found the cement plaster attached to 1 inch mesh strips fixed to adobe walls with rusted large nails (Chambers 1981, 17). Other cement removed was described as pink cement with thicknesses ranging from ¼ to 1/2 inches. These were carefully removed with a pointing trowel and a builder's saw. Some of the cement removed from the exterior dome was replaced with lime plaster 2 inches wide and whitewash was applied. The whitewash proved to be an unsuccessful treatment, since it did not adhere to the surface (Miller 1985).[35]

Figure 25 Cement removal procedures on the exterior walls consisted of cutting on a grid pattern with builder's saws equipped with masonry blades. Source: Chambers, George J. Tumacacori Preservation Project: Field Activities 1977, 1978, and 1979. Western Archeological Center, 1981, 26.

The new lime plaster mix consisted of 1 part lime paste, 1.5 part fine soil, and 4 parts washed mortar sand. The coarser sand was used to match that of the original plaster. Lime mortars used a similar mix, except for 4 parts instead of 5 parts sand. "Pebble lime" (quicklime) was acquired from the Paul Lime Plant in Arizona, and slaked on site (Chambers 1981, 20-21).

To treat the exposed adobe undergoing surface erosion, mud plaster, lime plaster and a chemically altered mud plaster were considered. One of the mud plasters considered was made to simulate the original materials, especially in terms of porosity. Another plaster mix was made to have a greater capillary potential in order to draw

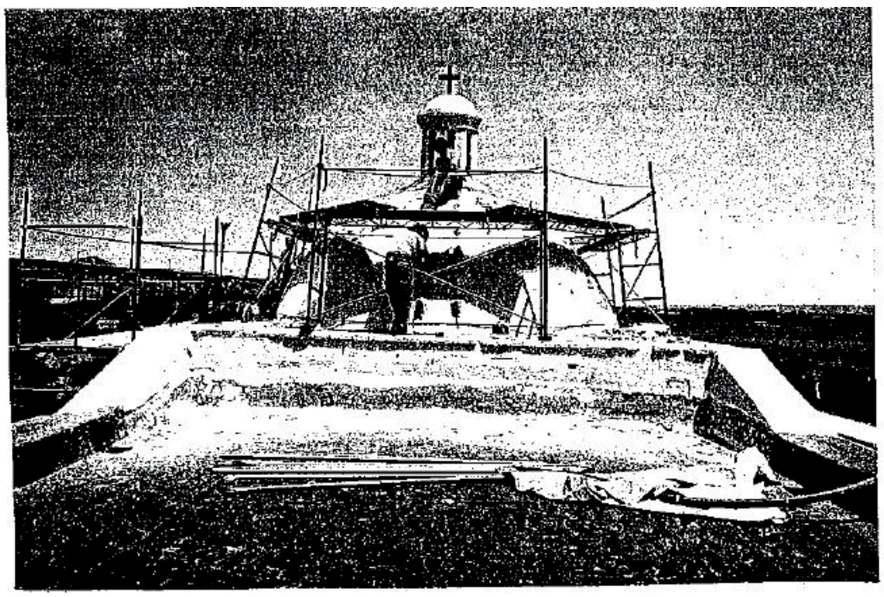
[35] This was presented by Hugh Miller in a news release article for the National Park Service on February 6, 1985.

moisture out of the walls. As a temporary measure, small holes that were found on the original lime undercoat of the exterior east nave wall were filled with mud mortar until plastering efforts could begin in 1978 (Champers 1981). To treat eroded areas, bowl shaped areas were cut back and were filled with small adobe bricks, 4 inches square by 10 inches long and mud mortar. Joints were recessed to provide keys for the plaster (Chambers 1981, 20). McHenry recommended a mix for mud plaster consisting of local soil tempered with ¼ volume of sand, and dry straw or grass to increase stiffness and adhesion. Floating was recommended at the end to fill possible shrinkage cracks (McHenry 1978, 12).

Cracks at the Mission San José have been monitored since 1977 using linear variable differential transformers (LVDTs), mechanical points, and additional leveling equipment. In addition to these methods, erosion and discoloration were monitored photographically (Crosby 1985). Crosby also tested samples of efflorescence and found that "most of the anionic salts were carbonates and sulfates, a significant amount of nitrates were also present. Chlorides were also present in a small percentage of the sample tests" (Crosby 1985, 73). The anionic salts did not show any direct correlation to the plaster decay.

The dome had major repairs done in 1979. The cement stucco, lime plaster and adobe were all removed, and 2.5 inches of lime plaster were applied to broken edges to match the original construction. Charles Yancey of Structural Engineering Group Center for Building Technology, expressed his concern to George Cattanach Jr. regarding the adobe and stone conservation, writing:

> The removal of the cement stucco which currently covers the exterior of the dome will have some effect on the interior dome conditions. If the stucco is replaced with a lime plaster the exterior heat fluctuations will affect the conditions on the interior more than at present. The difference may be insignificant but a slightly greater temperature fluctuation will probably result (Yancey to Cattanach 1979, 25).[36]



All cement plaster was removed from the dome and replaced with lime plaster.

Figure 26 Major dome repair and replastering with lime plaster. Source: Chambers, George J. Tumacacori Preservation Project: Field Activities 1977, 1978, and 1979. Western Archeological Center, 1981, 52.

After the lime wash application, a traditional water repellent of two coats of modified white wash was applied to the dome consisting of 8 gallons of lime paste with 10 gallons of water, 12 pounds of table salt, 6 ounces of powdered alum in 4 gallons of hot water, 1 quart of molasses after 30 minutes mixing and finally 12 ounces of

[36] This was included in a letter written by structural engineer, Charles Yancey, to George S. Cattanach, Chief of Division of Adobe and Stone Conservation on July 24, 1979.

formaldehyde. One gallon of whitewash was expected to cover 200 square feet and last for two to three years (Chambers 1981, 45).

### 2.3.3 Conservation Treatments: 1980s

Several methods were used in the 1980s restoration campaign, such as Acryloid B-72, Rhoplex and PVA emulsions for plaster consolidation. These treatments were mostly carried out by NPS architect Tony Crosby. He found loose, flaking gypsum and organic stains on the dome as well, and also investigated several cracks that were later repaired. It was later concluded by Crosby that the rate of deterioration increased considerably after Gettens and Steen’s conservation and restoration work in 1949. However, when the University of New Mexico compared 1949 images of the interior plaster and 2011, they essentially concluded that these had endured little loss over time (Porter et al. 2013).

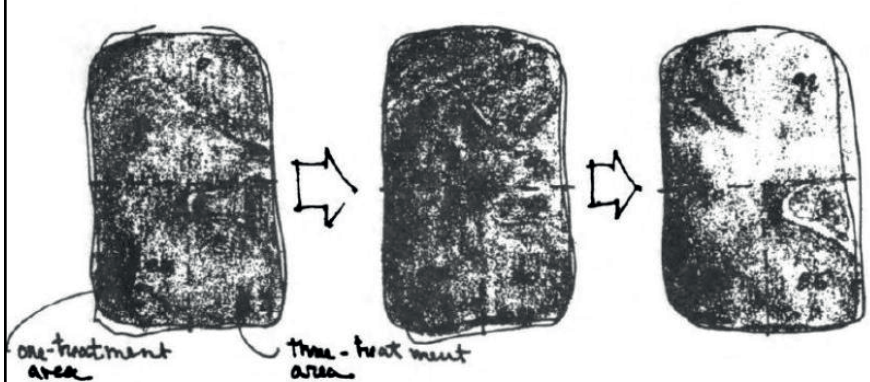



Figure 7: Back side of plaster Sample B showing visable capillary rise and relative surface moisture readings after 1 1/2, 2 1/2, and 4 hours, respectively. The blue areas are those which appear to be wet.

Figure 27: Diagrams showing efflorescence formation. Source: Crosby, Anthony. Historic Structure Report: Tumacacori National Monument Arizona, 1985: 184.

B-72, an ethyl methacrylate-methyl acrylate copolymer was tested in the interior prior to application and was considered a more effective treatment during the testing period than barium hydroxide (Crosby 1985, 82). B-72 was also used at plaster edges to reattach gypsum wash. Missing plaster ground was reconstructed using a thick lime putty, calcium hydroxide and a fine sand at a lime-sand ratio of approximately 1:4 by volume (Crosby 1985). Other methods used during the stabilization of the plaster edges included the injecting of a PVA (polyvinyl acetate) emulsion, or methyl methacrylate fixative, behind detached and flaking plaster layers (Crosby 1985). Additional treatments for the interior plaster used unamended lime plaster, plain water, and tissue (Raithel 1982).[37]

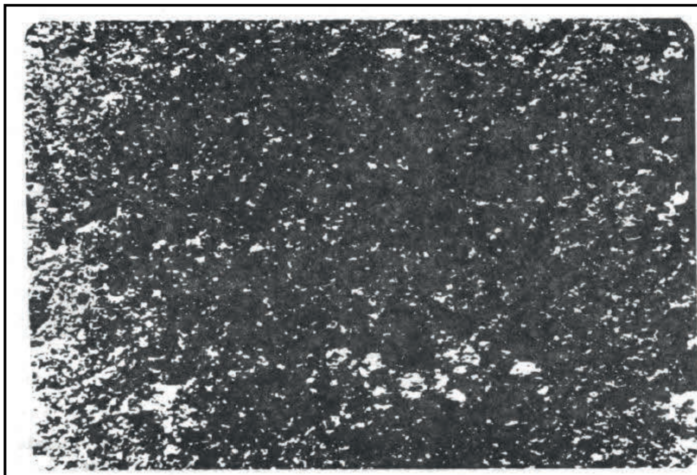


Figure 6: Detail of the center right portion of plaster Sample B showing the remains of some Acryloid B-72 which remained on the surface. Scale: approximately four times actual size.

Figure 28: Plaster showing remain of Acyrloid B-72 treatment. Source: Crosby, Anthony. Historic Structure Report: Tumacacori National Monument Arizona, 1985: 183.

PVA was also injected behind the lime plaster in order to attach it to the adobe substrate. This method was not completely successful. The PVA emulsion was deemed

37 This was included in a memorandum prepared by Kenneth Raithel, Jr., Assistant Manager, for the Regional Director of the Western Regional Office on December 6, 1982.

successful in certain areas, while in others the PVA penetrated through the surface layer (Crosby 1985, 65). Some recommended the use of nylon screws famously used on Italy's mural paintings (Raithel, 1982).[38] Other plaster edges were treated using a 2 to 5% solution of Rhoplex.

Painting conservators from the International Center for the Study of the Preservation and Restoration of Cultural Property (ICCROM) participated in the conservation of the Mission San José de Tumacácori during the summer of 1982, completing 60% of the work. The exterior dome plaster and the interior walls were damaged during the winter of 1982, which brought heavy rains followed by freezing night temperatures.

> The plaster tends to reconsolidate as warmer and drier weather arrives in the spring, making it difficult to detect the damaged areas if an inspection is not made before drying takes place (…) torrential rains totaling 9.07 inches (two-thirds) the anticipated annual precipitation) turned the church exterior into a sponge (…) some of the interior conservation work was damages as a result of this entry of water (Sewell 1984, 1).[39]

In August of 1985, the dome was repaired again using lime plaster painted with several coats of a vinyl-acrylic-latex base exterior masonry solution called Vin-L-Tex® (Unknown Tumacacori Mission Dome 1986, 2-3).[40] The repairs made to the dome were later questioned in 1985 by Hugh Miller as he was assessing the current condition. Miller

---

[38] This was included in a memorandum prepared by Kenneth Raithel, Jr., Assistant Manager, for the Regional Director of the Western Regional Office on December 6, 1982.
[39] This was included in a memorandum prepared by Joseph L. Sewell., Tumacácori Superintendent, for the SOAR, WACC and DSC offices on April 4, 1984.
[40] Author and origin of documents is unknown. The title of the document is "Tumacacori Mission Dome-Project Update History".

believed the waterproofing coating covered structural failures (Miller memo 1985).[41] Burnt adobe bricks that were installed in 1979 on the mission's west ledge were also failing citing "poor firing". The edges of these bricks (exterior) deteriorated quickly and were allowing rainwater that fell on the ledge to run through the interface of the adobe wall and lime plaster (Chambers 1986, 1).[42] Plaster and paintings were also found to have detached from the dome (Albert 1988).[43]

### 2.3.4 Conservation Treatments: 1990s to 2000s

During the 1990s, detached plaster was consolidated with injections of a 15% solution of Rhoplex®, water and alcohol. Rhoplex alone is generally not recommended for this use since the detached layers require a gap filling material. For a stronger adhesion, a higher concentration of Rhoplex is required, but this would potentially stain the plaster (Porter et al. 2013, 8). Plaster reattachment treatments in 1992 also included injection grouting with an Italian commercial grout, Ledan®, used to fill voids in masonry walls and to reattach layers.[44] Ledan® injection grouting lasted a week. Losses were covered with 1 part lime to 3 parts sand mortar.

---

[41] This was included in a memorandum prepared by Henry Miller, Assistant Manager, for the Regional Director of the Western Regional Office on December 6, 1982.

[42] This was included in a memorandum prepared by George J. Chambers, Cultural Resource Specialist, for the Chief of Division of Archeology on March 12, 1986.

[43] This was included in a memorandum prepared by Lewis S. Albert, Regional Director of the Western Region, for the Superintendent of Tumacacori and Chiricahua on November 2, 1988.

[44] Ledan® is a lime based ready-made mortar sometimes used for grouting cracks in painted plasters. Other variations of Ledan®, such as Ledan TB1® is composed of Portand cement and calcium hydroxide as the binder. When used as a filler, Ledan TB1® is mostly composed of quartz powder and slate powder. Technical information is found on the Tecno Edile Toscana website.

In the early 2000s, ammonium caseinate was used for reattachment purposes. This treatment had poor gap filling properties and like Rhoplex®, required surfaces to be in close contact. With time, ammonia casein solutions yellow and become brittle, insoluble and irreversible. Ethyl silicates were used as a consolidant as well. Resins and previous treatments were removed and cleaned with the use of acetone and ethanol. Efflorescence was treated using cellulose poultices with deionized water. Repairs were also made by Tohono Restoration using 3.5 parts lime to 1 parts sand (Porter et al. 2013, 9).

Other stabilization projects extending over the site took place in 2009. Dried mud was found running down the south interior window over on the sanctuary's west side. Evidence of cracks and water leaking was visible on the south side of the mission's exterior. To repair and fill the cracks, different mixes consisting of 3.5 parts sifted sand and 1 part lime were used (Unknown Sanctuary Leak Report 2009, 3).[45]

[45] Author and origin of documents is unknown. The title of the document is "Report on plaster cracking and leaks associated with the west sanctuary window", prepared July 6-8, 2009.

Figure 29: Repairing plaster on the exterior of the west sanctuary window, cornice and dome apron. Source: Tumacácori National Historic Park. Unknown Publisher. July 6-8, 2009: 3.

Figure 30: Report on Plaster Cracking and Leaks Associated with the West Sanctuary Window. Source: Tumacácori National Historic Park. Unknown Publisher. July 6-8, 2009: 3.

### 2.3.5 Conservation Treatments: 2010s to present

Heavy rains once again accelerated plaster loss in the dome interior in January 2010. The winter storm produced four inches of rain. There was roof leakage to be repaired as well as adobe failure, and partial collapse of the window around the Sanctuary. The total plaster area lost was 23.4$m^2$ around west the Sanctuary window. A few days after the storm, a scratch coat was applied on the east exterior Sacristy wall (Arendt 2010, 2). Three months later, major repairs were made on the upper west exterior Sanctuary wall. Bricks were replaced and were keyed to the existing wall by drilling into the adobe with a ½ masonry bit. The mixture used initially for repairs was considered to be far too clay rich which began cracking and pulling away from the wall. To adjust this formulation, 3 parts clay: 2 parts sand and 1 part gravel were used (Arendt 2010, 7).

In 2011, the School of Architecture & Planning at the University of New Mexico were invited to perform an assessment and stabilization of the painted plasters in the Mission San José de Tumacácori. As observed in Figure 31, flaking gypsum layers were restored by using wet strength tissue adhered with 5% gelatin in water while larger fragments made use of crepeline in a 10% solution of B-72 in acetone (Porter et al. 2013, 50). Injection grouting in the dome was composed of 1 part hydrated hydraulic lime (NHL 3.5) and 1 part ceramic microspheres. The grout was injected into the voids using 10ml and 30ml syringes depending on the width of the void or crack. Setting time for the grout was about 10 minutes, and it was expected to cure for a year (Porter et al. 2013, 51). To stabilize the plaster edges, some were injected with a 5% solution of El Rey Superior 200 in distilled water. UNM also monitored environmental conditions in the dome, including temperature, relative humidity, and surface temperature.

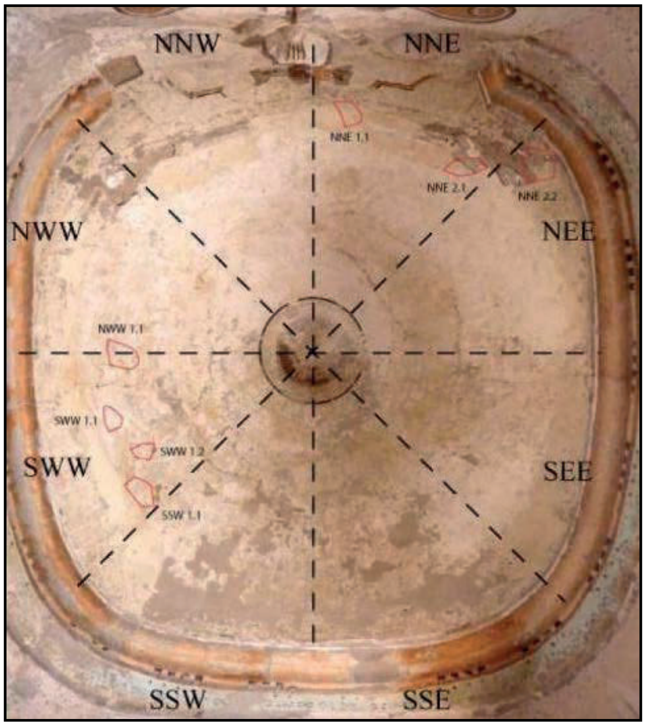



Figure 32: Salt sample dome locations. Source: Bass and Porter. Assessment, Emergency Stabilization and Treatment of Painted Plasters in the Mission Church at Tumacacori National Historic Park, School of Architecture and Planning, 2012: 32.

Figure 31 Flaking yeso finishes on the plaster were treated using a 1982 technique, which consisted of a 5% solution of gelatin in warm water. Source: Bass and Porter. Assessment, Emergency Stabilization and Treatment of Painted Plasters in the Mission Church at Tumacacori National Historic Park, School of Architecture and Planning, 2012: 53.

Figure 33 : The poultice, composed of cellulose and distilled water, is being applied at Tumacácori to remove salts. Source: Bass and Porter. Assessment, Emergency Stabilization and Treatment of Painted Plasters in the Mission Church at Tumacacori National Historic Park, School of Architecture and Planning, 2012: 48.

## Chapter 3: Grout Injection Used for Repair on Earthen Buildings

The purpose of this chapter is to provide an overview on injection repair grouts for earthen buildings, focusing especially on grouts composed of soil since less research has been done on the subject in comparison to air lime- and hydraulic lime-based grouts. Although the application of grouts for Tumacacori is nonstructural, i.e., for plaster reattachment, the literature on structural repairs has been included and discussed. Throughout the chapter, amended grouts, modified grouts, and stabilized grouts are used interchangeably, as well as unamended and unmodified grouts.

### 3.1 Brief History on Grout Injection Used for Repair on Earthen Buildings

Scientific research on injection grouting for conservation uses began with lime based grouts developed by ICCROM (Ferragni et al. 1984). A few years later, scientific testing of additives to improve grout performance commenced in the field (Ferragni et al. 1984). ICCROM researchers concluded that a moderately hydraulic lime and crushed brick (1 to 1 by volume ratio), and the addition of an acrylic emulsion to increase adhesion displayed good performance. Laboratory specifications were also defined for the ideal properties for grouts based on the use of hydraulic lime (Ferragni et al. 1984).

For nonstructural grout repairs, conservators studied in-situ stabilization such as plaster and mosaic reattachment using hydrated lime with casein, and later with PVAC, a synthetic resin emulsion (Ferragni et. al 1984). By 1986, a low-alkali hydraulic lime amended with PVAC, began to be used to reattach murals on earthen plaster by three

ICCROM researchers: Schwartbaum, Na Songkhla, and Massari. It was not until 1990 that modified soil based grouts were proposed to fill cracks in adobe (Roselund, 1990). Following the ICCROM research, several commercial grouts became available after the 1990s. Although these products were easy to prepare, their compatibility with historic materials was not always guaranteed and they have been found to display excessive strength and high salt content (Biçer-Simsir et al. 2009).

Research at The Architectural Conservation Laboratory on hydraulic lime grouts formulated with fine sand, glass or ceramic microspheres, and hydraulic lime with and without the use of acrylic emulsions was begun in early 2000 with good results (Matero et al. 2003). Regardless of the extensive research on hydraulic lime based grouts in the past few years, there is still a need for further research.

**3.2 Challenges with Grouting**

Failure of structural and nonstructural grouts can be due to many factors. Significant causes include: shrinkage during drying cycles which causes the grout to loose adherence and therefore fail (Vargas et al. 2008) and stress fatigue and failure during hygric and thermal fluctuations where the grout and substrate meet (Simon and Geyer 2008), and If good chemical, physical and mechanical compatibility is not achieved between the grout and the plaster/adobe layers, moisture can enter the porous system, causing dissolution and re-crystallize soluble salts present in the plaster (Padovnik et al. 2016).

Minor components in the grout formulation may be modified for testing purposes, but most researchers and scholars agree that reproducible testing instead of case-dependent research is more important than the type of grout used (Simon and Geyer 2008, 260). One such problem applies to earthen grouts, as few formulations have been tested using standard testing. If such is the case for unamended earthen grouts for the use of structural repairs, less standardization of test methods has been developed specifically for non-structural grouts in general (Padovnik et al. 2016).

Laboratory specifications for hydraulic lime based grouts have been researched to a greater degree, tested and applied by ICCROM researchers and conservators in the field, and more recently by The Getty Conservation Institute. However, most ASTM standards focus on the preparation of cement mortars. The Getty publication suggests that more appropriate and relevant procedures be standardized for non-cementitious grouts (Bicer-Simisr et al. 2009).

### 3.3 Structural and Nonstructural Repair Grouts

Different grout formulations have been utilized to conserve earthen architecture. However, most of the research and application has focused on the structural use of grouts, such as repair of structural cracking from seismic activity threatening a building's stability (Vargas et al. 2008). In these instances, grout injections are used to re-establish the building's monolithic character and structural strength with minimal disruption of its surfaces. Less research has focused on nonstructural grout repair, such as reattaching delaminated layers using soil-based formulations. This loss of adhesion can occur between the substrate and the plaster layer, and in between plaster layers resulting in bulging, disintegration, delamination and detachment of the surfaces (Padovnik et al. 2016). Cave 85 of the Mogao Grottoes located in Dunhuang, is one such case where detached layers were treated using a soil based grouts, and egg whites as the additive.[46] The painted Buddhist caves of Mogao were suffering from separation and partial collapse of their painted earthen plasters from a rock support (Rickerby et al. 2004, 471).

Overall, grouts have repeatedly been used for earthen buildings to readhere detached layers by filling in voids, cavities and cracks in the plaster. What has changed in the past years is the type of binder, filler and additives used for grouting.

### 3.4 Amended and Unamended Earthen Grouts

Two types of earthen grouts used for structural repair are amended earthen grouts, using mineral (lime or cement) or polymer amendments (PVA) and unamended soil grouts based primarily on the clay found in the soil as the binder. While a significant portion of the research focuses on amended or modified earthen grouts, others have tested the use of unamended earthen grouts to restore strength on earthen structures (Vargas et al. 2008; Silva et al. 2012; Lourenco et al. 2013). Many have gravitated towards modified earthen grouts because by incorporating binders with lime, cement or gypsum, shrinkage can be controlled and higher strengths achieved.

[46] Deterioration of the Mogao Grottoes and conservation treatments were addressed by the Dunhuang Academy and the Getty Conservation Institute.

Past research has tested the application of soil grouts in adobe assemblies (Simon et al. 2008; Vargas et al. 2008; Padovnik et al. 2016).[47] Assemblies made with unstabilized soil grouts, and soil and gypsum grouts proved to be stronger than those assemblies composed of lime or cement additives (Vargas et al. 2008). However promising unstabilized soil grouts might seem, not enough testing has been performed (Silvia et al. 2012).

In Simon's testing of amended grouts, the three different soil types researched were local adobe from a nearby site and two typical building soils that matched the case study's soil. Selective additives included: carboxy methylcellulose, Tylose MH 300, Klucel E, rabbit skin glue, glass microballoons, and quartz powder (Simon et al. 2008). Ultimately the best performing amended grout contained local adobe soil with a particle size of 150 µm, quartz, powder and Tylose additives.[48] [49]

Other researchers, such as Silva, Schueremans, Oliveira, Dekinng and Gyssels, tested both modified (amended) and unmodified (unamended) grouts for repairing structural cracks using amended soils (Silva et al, 2012). One grout consisted of earth, silica sand, fly ash and hydrated lime. Another modified mud grout consisted of clay

[47] The grout was tested by replicating the substrate, in many instances adobe, and arranging it in a sandwich like assembly joined together by the grout. In some of these assemblies, sand was clumped on the wet mockups and removed once dry to simulate cavities. Afterwards, grout was injected and the mock-ups were cut in order to analyze the degree of filling and shrinkage cracks (Simon et al. 2008).

[48] Tylose MH 300, or methyl-hydroxyethyl cellose with standard etherification, is a water-soluble non-ionic polymer. It is typically used as an additive to provide water retention, adequate binding, thickening and colloid properties.

[49] Infrared thermography imaging, was used to confirm complete gap filling.

powder, lime and wallpaper paste. Overall, the modified grouts were more successful than the unmodified grouts, which presented excessive shrinkage (Silvia et al. 2012).

A year later, Silva, Oliveira, Lourenco, Schueremans and Miranda tested two grouts: an "artificial" soil grout composed of kaolin and limestone powder, and a "natural" soil grout composed of soil with a maximum particle size of 0.18mm (No.80 sieve) and limestone powder (Silva et al. 2013, 2-5). Both grouts included the addition of sodium hexametaphosphate to improve fluidity.  Overall, the "natural" soil grout (B) had better adhesion, had a better recovery rate (66%) for shear strength, and was stronger than the artificial grout.

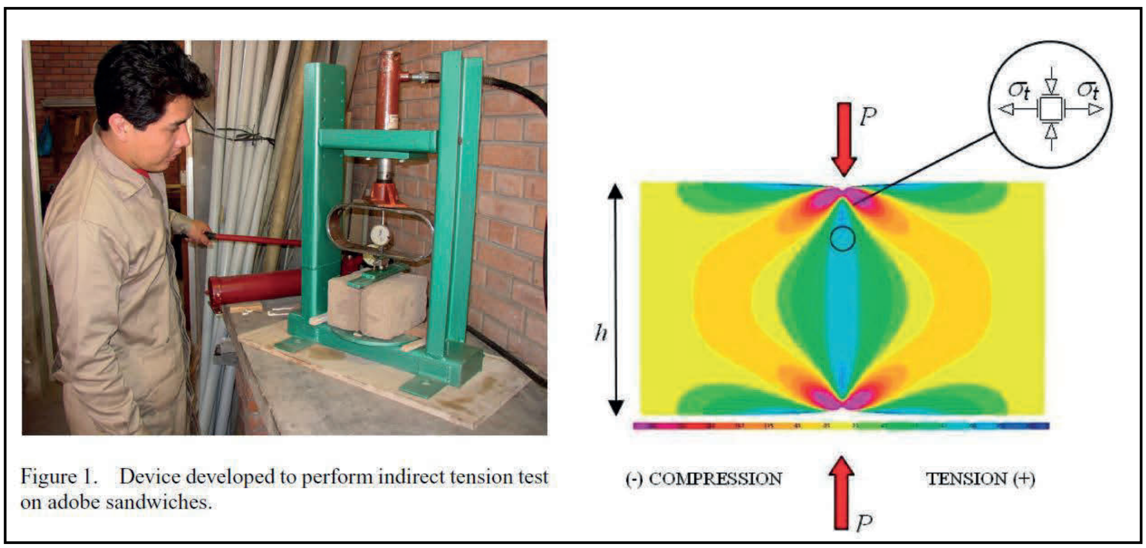



Figure 34: Vargas testing for tensile strength on adobe sandwiches. Source: An Experimental Study of the Use of Soil-Based Grouts for the Repair of Historic Earthen Walls and a Case Study of an Early Period Buddhist Monastery. Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage. The Getty Conservation Institute and the Mali Ministry of Culture, 1096.

Other scholars, such as Vargas et al. (2008) tested modified and unmodified mud grouts and determined the latter had a better adhesion capacity as well, recommending the use of unmodified grouts over modified grouts. Modified grouts are said to be extremely stiff which may not satisfy the mechanical compatibility of lime and adobe plasters. Additionally, unmodified earthen grouts have proven to provide better adhesion in adobe walls; their drying shrinkage may not affect adhesion to the substrate (Lourenco et al. 2013).

### 3.5 Earthen Grout Design

Achieving compatibility of the grout with the original adherents is a difficult task, since often the components are of more than one material, i.e., lime plasters on adobe. The commonly used binder, hydraulic lime, is often used due to its compatibility with original lime-based materials, but it can also be extremely strong.[50] [51] In the case of Tumacácori, the lime plaster has detached due to the deterioration of the adobe at the interface with the plaster. In order to compensate for this failure due to adobe deterioration, the decision was made to look at soil-based grouts as both a material and method of remedial repair. Local naturally occurring soils rather than formulated artificial soils were only considered in order to satisfy the larger requirement of practicality of material access and the concept of sustainability as defined by "local solutions" to conservation problems (Matero, personal communication).

Required properties for designing soil grouts, such as strength, fresh state rheology and stability, chemical stability, and microstructure, are determined by the

[50] With lime based grouts, properties achieved depend on the chosen binder: such as hydrated lime or hydraulic lime.
[51] Additionally, matching the composition of original plasters may pose a problem with injection grouts, since the same composition does not guarantee well working properties, such as flow and it may also introduce additional damage and durability problems (Bicer-Simisr, 2009; Lourenco et al. 2013).

characteristics of the soil use. Adjusting the composition in order to improve some properties may alter or jeopardize other properties (Silva et al. 2012). Compatibility does not always translate into using the same materials as the adherends since a grout is delivered in a manner very different from the original construction assembly or process. "…the same materials cannot be automatically transferred to a grout mixture, which needs to be easily injected, and substitute materials may need to be added to enhance grout performance" (Rickerby et al. 2004, 472).

### 3.5.1 Methodology and Testing Schedule

The first step to design grouts is to define the performance requirements for the grout. These can be separated into mechanical behavior and durability of the injected substance requirements. Mechanical behavior requirements means that a grout must display good injectability and bonding properties in order to flow through small cracks and voids. The mechanical properties sought for the grout depend on the structure's level of deterioration or damage, as this will decide what the behavior of the injected structure should be (Silva et al. 2009). An overall design methodology for earthen grout injections does not yet exist. However, many reference Griffin's work in 1997, 1999 and 2004, as a means to developing one.

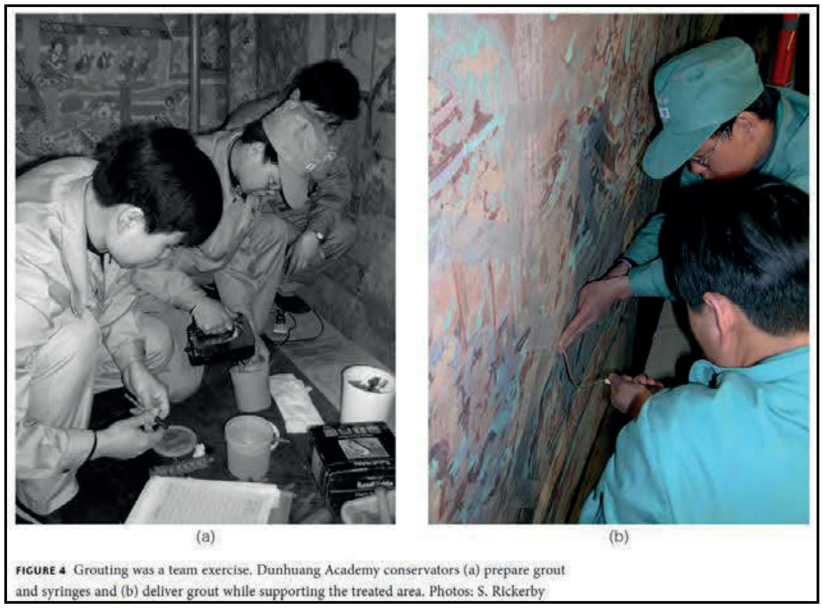



Figure 35: Grouting delaminated earth plasters at Cave 85. Source: Implementation of Grouting and Salts-Reduction Treatments at Cave 95 Wall Paintings. In Conservation of Ancient Sites on the Silk Road, Second International Conference on the Conservation of Grotto Sites (Rickerby et al. 2008, 483).

For the Dunhuang, Cave 85 Project, working properties and artificial aging were tested.[52] Performance characteristics included the following: minimal volume change, similar water vapor permeability to plaster, low density, retreatibilty, good adhesion, and similar mechanical strength to plaster (Rickerby 2004, 474).[53] Working properties, while the grout is in a liquid state, included: injectability, viscosity, setting time, low toxicity, slow water release, and minimal water content (Rickerby et al. 2004, 474).[54]

---

[52] Characterization of the mud collected from the Daquan River was performed, as well as characterization on the plaster samples. These samples were found to be minerologically identical, thus insuring compatibility. The riverbed mud was used as the grout binder. The filler materials were preselected based on existing deficiencies of the earth binder.

[53] Like Tumacácori, a grout with a very low wet and dry density was required. Similar to Tumacácori, Cave 85's plaster had been previously subjected to several repair attempts, such as pinning which concentrated stresses on the weakened plaster layers.

[54] More than eighty grout formulations were preliminarily evaluated, while only a few were subjected to full testing.

### 3.5.2 Earthen Grout Properties

Fluids, such as grouts, exhibit time dependent change in viscosity, known as thixotropy. The longer the grout is subjected to shear stress, the lower its viscosity, which is considered a desirable property. An increase in an earthen grout's viscosity during mixing may occur when formulated without additives. On the other hand, modified grouts with additives decrease in viscosity during mixing time, requiring up to three days to recuperate. This in turn implies that aside from additives, stirring plays an important role in acquiring a certain viscosity level, as agitating the grout mix alters the grout's suspension (Simon, 2008).

Soaking the grout can also decrease the viscosity, but stirring it speeds up its production. According to Simon, stable suspensions can only be acquired with grain sizes measuring 125 µm (Simon and Geyer 2008, 263). Mixing for long periods of time can help achieve lower viscosity and good fluidity for modified grouts. Modified earthen grouts and soil grouts made with a very high water content attain adequate fluidity, but the fluidity also decreases viscosity and the likelihood of excessive drying shrinkage on the hardened grout increases (Simon et al. 2008; Silva et al. 2012).

Overall, a high amount of clay increases chances of shrinkage and cracking therefore a careful selection of the soil should have an adequate ratio of clay/silt and sand content (Simon, 2008). The most common clay minerals are kaolinite, illite and montmorillonite. Reducing the amount of clay in an earthen grout reduces the demand for water in the mix (Silva et al. 2012). Researchers have been able to reduce the amount of water needed by incorporating kaolin suspensions with limestone powder (Silva et al.

2012). Others, such as Iyer, have determined the ideal soil grout has low viscosity and high homogeneity, 2.5:1 solid to liquid ratio. Also, stable clays, such as kaolinite, do not swell in the presence of water and have a low ion fixing capacity (Iyer 2014).

Another frequent method to reduce shrinkage is to incorporate a dispersion agent, such as sodium hexametaphosphate, into the water (Lourenco et al. 2013). Some researchers, have expressed concern when employing water as a fluidizer in an earthen grout formulations. The latter may result in serious implications, such as the activation of soluble ions in an already salt contaminated plaster (Rickerby et al. 2004, 471).

Regarding the clay content in the mix of the grout, some results have demonstrated that the flexural and compressive strength that the grout can achieve depends on a higher clay content. Basically, the rheological behavior of the soil grout is dependent upon the colloid behavior of the clay particles. A higher clay content in the grout means a higher fluidity, drying shrinkage and swelling, but good binding. However, the fluidity of the grout should be limited. Fluidity is also necessary to develop adhesion and strength in the grout, so a careful balance of the clay content should be achieved for a successful grout (Silva et al. 2012; Silva et al. 2009).

It's also not ideal for a potential grout to have a low solid fraction, as this would result in high shrinkage. It is also important to add coarse aggregate in order to create an interlocking effect and increase cohesive strength within the grout. Conversely, aiming for a larger volumetric solid fraction would create a grout with poor injectability properties, making its injection at low pressure difficult (Silvia et al. 2012).

Figure 36: Figure 34: Grouting of west window plaster at Tumacácori. Cotton was used to catch overflows and prevent further detachment due to any pressure exerted by the grout. A solution of 1 part NHL 3.5: 1 part ceramic microspheres was used. Source: Assessment, Emergency Stabilization and Treatment of Painted Plasters in the Mission Church at Tumacacori National Historic Park, School of Architecture and Planning (Bass and Porter, 49).

Fillers used can help to reduce shrinkage numbers and control the grout's mechanical strength. For the dome at Tumacacori, Bass and Porter chose a grout mix containing one part hydrated hydraulic lime (NHL 3.5) and one part ceramic miscrospheres by volume (Bass et al. 2013, 50).[55] Glass microspheres have also been used as lightweight fillers for earthen grout formulations. While exhibiting a low wet and dry densities, and promoting a good viscosity and injetability, their spherical shape, reduces the grout's internal cohesion. The greater the amount of glass microspheres, the weaker the solution (Rickerby et al. 2004, 475).

[55] The grout mixture was designed to act as a void filler and as an adhesive for the detached plaster layer; they have a low water content which can minimize shrinkage but are fluid enough to flow. These can also set in oxygen deprived conditions within the walls, have a water vapor transmission rate similar to the existing material, and can achieve a sufficient bond strength or shear strength while being lightweight at the same time (Bass and Porter. 2012).

Additives and extended mixing is not only successful in decreasing viscosity levels and achieving good flow but also increasing grout strength, such as the use of methylcellulose additives in earthen grouts. Tylose is another additive that has proven to increase pull-off strength (Simon et al. 2008).

For paint reattachments, compatible earthen grout with additives such as egg whites have been successfully employed. The use of egg white is described by Griffin's research as a strong adhesive that improved injectability and viscosity, augmenting rather than substituting for clay binding properties" (Rickerby et al. 2004, 476;Griffin 1999, 24–31, 39–42, 44–45, 51–60, 63–65). The egg white also reduces the amount of water released from the grout.[56]

However, the use of additives for strengthening purposes is refuted by other scholars such as Vargas. His testing concluded that assemblies repaired with unamended grouts were 20% more likely to be stronger than the original samples. In this instance, additives were not necessary for the grout to recover the strength of the cracks. Some grouts have been formulated with PUCP soil and soil stabilized with gypsum. (Vargas et al., 2008).

[56] Egg white was whisked and introduced into the mixture, as an air-entraining foam.

**Table 1 Earthen Grout Components and Their Potential Disadvantages**

| Grout Component | Function | Potential Disadvantages |
|---|---|---|
| Binder earth | bind the solid components of the grout mixture | • high wet and dry densities<br>• long drying time<br>• high shrinkage |
| Fluidizer water | activate clay component | • damage to water-sensitive/soluble plasters and paint materials<br>• activates salts |
| Filler(s) | • provide bulk and enhance internal cohesion<br>• counter shrinkage<br>• improve porosity and water vapor permeability<br>• reduce density<br>• improve viscosity (injectability)<br>• increase drying rate | • may compromise compatibility<br>• may result in too low or too high strength |
| Additive(s) | modify grout properties further (optional) | • may compromise compatibility |

Figure 37: Potential disadvantages of earthen grout components. Source: Development and Testing of the Grouting and Soluble-Salts Reduction Treatments of Cave 85 Wall Paintings. In Conservation of Ancient Sites on the Silk Road, Second International Conference on the Conservation of Grotto Sites (Rickerby et al. 2008, 473).

Durability of the injected structure is achieved with intimate contact between the grout and the wall. The use of earthen grouts implies the use of raw materials that closely resemble the plaster's support on the substrate. Bonding is also key for a successful grout repair selection, as it limits unwanted chemical reactions (Silvia et al. 2009). In particular, well-designed earthen grouts should be fluid enough, exhibit low shrinkage and strong bond equal to its own cohesive strength for successful repair (Iyer, 2014).

### 3.6 Conclusive Remarks

Both hydraulic lime grouts and earthen grouts have proven successful depending on the specific grout mix. Preference for hydraulic lime grouts is undoubtedly due to the fact that hydraulic lime is readably available in the market as a binder as well as in prepared commercial conservation grouts. Another aspect contributing to the popularity of lime based grouts is the perceived drawbacks of soil based grouts, such as excessive shrinkage and low strength, which have limited their use as a binder for conservation purposes.

Where lime based grouts have been employed, some have resulted in poor adhesion between the lime and earthen materials (Griffin 1999, 13, 60). Silvia et al. (2012) argue that adding hydraulic lime as a binder can greatly increase the grout's modulus of elasticity making the grout less compatible to the existing material. Grouting with hydraulic lime as an additive is not always compatible with the shrinkage and swelling behavior of earthen structures as the bond between the grout and the existing adherend may be weakened by the water introduced. When water is introduced, the water in the grout can become absorbed by the wall, shrinking the grout after drying (Silva et al. 2009).

Soil-based grouts instead must be formulated and tested for each case when using locally sourced materials; however these can display true compatibility when used with locally sourced adobe substrates. Material compatibility should be possible by developing an earthen grout based on local soil sources that match those sources used for construction such as the adobe. If local soil grouts can be formulated that display good injectibility and low shrinkage, their solid state should display similar strength, hardness, abrasion resistance, and water vapor transport values as the adobe itself. (Simon et al. 2008; Vargas et al. 2008; Silvia et al. 2012).

# Chapter 4: Methodology

| Phase 1 | Phase 2 | Phase 3 |
|---|---|---|
| Material Characterization<br>Adobe and Plaster Analysis | Grout Preparation | Mock-ups |
| **Adobe Samples:**<br>**1-**Retrieve adobe samples from site<br>**2-**Crush samples (mortar and pestle) and sieve them in order to characterize the soil used to prepare the bricks.<br>**3-**Perform the following tests: (Same for Soils)<br>-Particle Size Distribution<br>-Plastic limit, Liquid limit (Atterburg Limits)<br>-Dry/wet sieving<br>-pH of Soil<br>-Organic Content<br>-Semi-quantitative Salt Analysis<br>-Methyl blue adsorption<br>**4-**Compare to soil samples collected.<br><br>**Plaster Samples:**<br>**1-**Plaster analysis (petrographic analysis) and compare to exterior plaster thin sections. (See Appendix A)<br>**2-**Recreate plaster sample for mockups.<br>1 type S hydrated lime: 5 sand:1.5 water<br>**3-**Let the plaster samples cure for 28 days.<br>**4-**Consolidate half the samples with 3 coats of nanolime and let cure for an additional 28 days. | **Soil Samples:**<br>**1-**Retrieve soil samples from site.<br>Soil A, Soil B (Tucson Pioneer soil) & Soil C (Rio Rico topsoil)<br>**2-**Perform the following tests: (Same for Adobe)<br>-Particle Size Distribution<br>-Plastic limit, Liquid limit (Atterburg Limits)<br>-Dry/wet sieving<br>-pH of Soil<br>-Organic Content<br>-Semi-quantitative Salt Analysis<br>-Methyl blue adsorption<br>**3-**Choose the sample that best performs.<br><br>**Grout Preparation:**<br>**1-**Grout Formulation:<br>2.5: 1 soil to HMP<br>(Soil sieved through ASTM sieve #10)<br>**2-**Perform the following tests:<br>Wet Grout Testing:<br>-Flow/ Viscosity<br>-Wet Density<br>-Drying Shrinkage Test<br>-Expansion & Bleeding<br>Hardened Grout Testing:<br>-Capillary water absorption<br>-Water retention<br>-Permeability (water vapor transmission)<br>-Splitting Tensile Strength | **Assembly:**<br>**1-**Prepare mockup samples with adobe, recreated cured plaster samples and chosen grout. Grout will be injected with a catheter tip syringe attached with a small tube.<br><br>a) Square Coupon (3.5" x 3.5") of scratch coat simulation (+ consolidation) + adobe + (selected earthen grout) 4 will have 1/2" gap, and 6 will have 1/4" gap.<br>b) Square Coupon (3.5" x 3.5") of scratch coat simulation (NO consolidation) + adobe + (selected earthen grout) 4 will have 1/2" gap, and 5 will have 1/4" gap.<br><br>**2-**Perform Shear Bond Strength (adhesion) on all assemblies. |

Table 1: Methodology Schedule. Source: Declet 2017.

## 4.1 Sample Retrieval and Material Characterization

The first portion of the research project involved analysis of the current conditions of the historic painted lime plaster located in the interior nave of the Mission San José de Tumacácori. A recent condition assessment of the interior plasters of the mission church performed by the University of Arizona, revealed detachment and cracking of the nave and lower sanctuary (UA 2011). Three soils from local sources used on site for repair were sampled with the help of Alex Lim, Exhibit Specialist and tested at the ACL. [57]

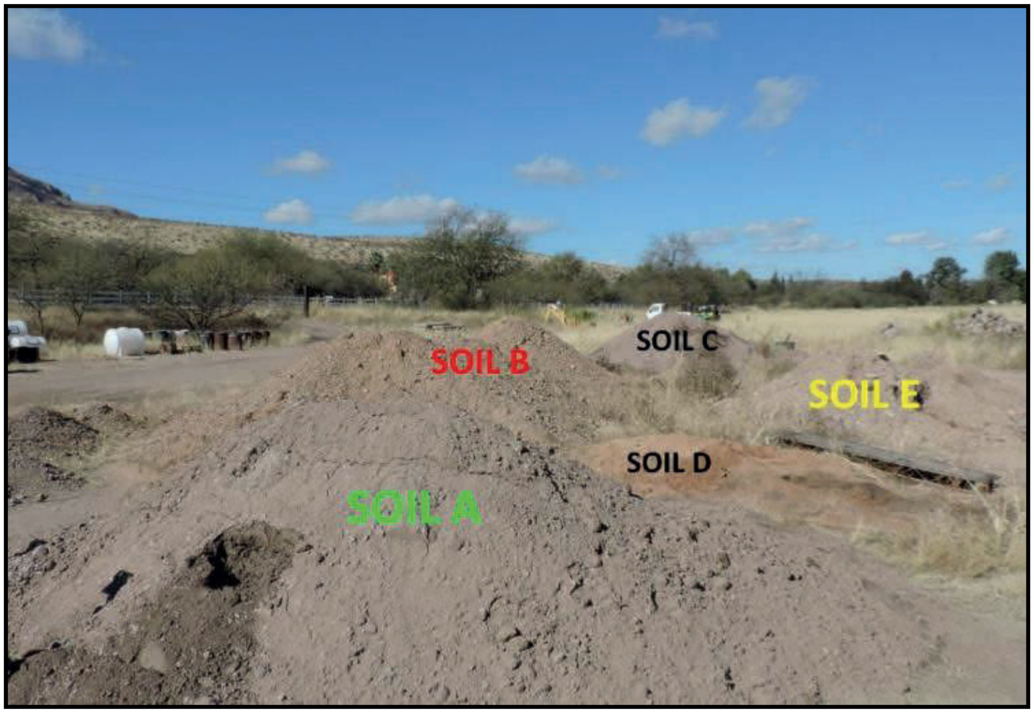



Figure 38: Soil retrieval location identification in Nogales, Arizona. Source: Declet 2017.

Once back at the laboratory, Phase 1 focused on material characterization of the local soil samples. Overall, the three soil types, adobe, mortar, and plaster were collected. The sample schedule for material characterization of both adobe and soils is listed below.

57 The local soils types selected at Tumacácori National Historical Park. Soil A and Soil B came from manufacturer Tucson Pioneer Soil. Soil E came from manufacturer Rio Rico Topsoil.

Table 2: Testing Schedule for Characterization of soil types and original adobe. Source: Declet 2017.

| Material Characterization Testing | Standard/ Reference | Minimum Quantity |
|---|---|---|
| Particle (grain) size distribution | ASTM C136-06 | 90g |
| Plastic Limit, Liquid limit, and plasticity index of soil | ASTM 4318 | 20g (Plastic); 100g (Liquid) |
| Combined dry/wet sieving | ASTM D422; ASTM D1140; Nityaa Iyer 2014 (P.36) | 150g |
| pH of Soil-Acid Solubility | ASTM D4972-13 | 10g (in water); 10g (in calcium chloride) |
| Organic Content Analysis | ASTM D2974-14 | 50g |
| Semi-Quantitative Salt Analysis | Merck Strips | 5g |
| Methyl blue adsorption test | AFNOR NF D 94-068-1998; Nityaa Iyer 2014 (p.57) | 60g |

## 4.2 Adobe and Soil Characterization

Original adobe samples TUMA S-7 and TUMA S-11 taken from the east nave wall were selected for characterization. This included performing several tests on the adobe samples in order to characterize the soil used to prepare the adobe and compare these results to the local soil samples collected. The samples were prepared first by crushing with a mortar and pestle. Afterwards a portion of the 463 g adobe sample was oven dried while a small amount was left to air dry in preparation for the Plastic and Liquid Limit Test and Methylene Blue Test. Soils A, B and E were already in soil form so no additional preparation aside from oven drying was necessary. These were subjected to the same characterization tests as the adobe.

The soil selected to make the grout should be similar to and therefore compatible with the original earthen substrate in order to achieve similar strength, water vapor permeability rates, and adhesion strength. The soil type's microstructure and rheology is analyzed through the following tests in order to do so. The soil will then compose the grout's binder which will be subjected to several tests. The optimal grout properties were organized within a test matrix. These included good distribution ratio of sand, silt and clay content in order to control shrinkage as well as pass through the desired injection orifice.

- **Particle Size Distribution**

The soil was classified by grain size, shape and sorting which define the soil's microstructure. Sieving followed ASTM C136-06. Using the percentage retained on each sieve, the soil's grain size distribution or granulometry were identified as either coarse sand (passing No.4 and retained on No.10), medium sand (passing No.10 and retained on No.40 sieve), fine sand (passing No.40 and retained on No.200 sieve) and silt and clay fines (retained in pan).

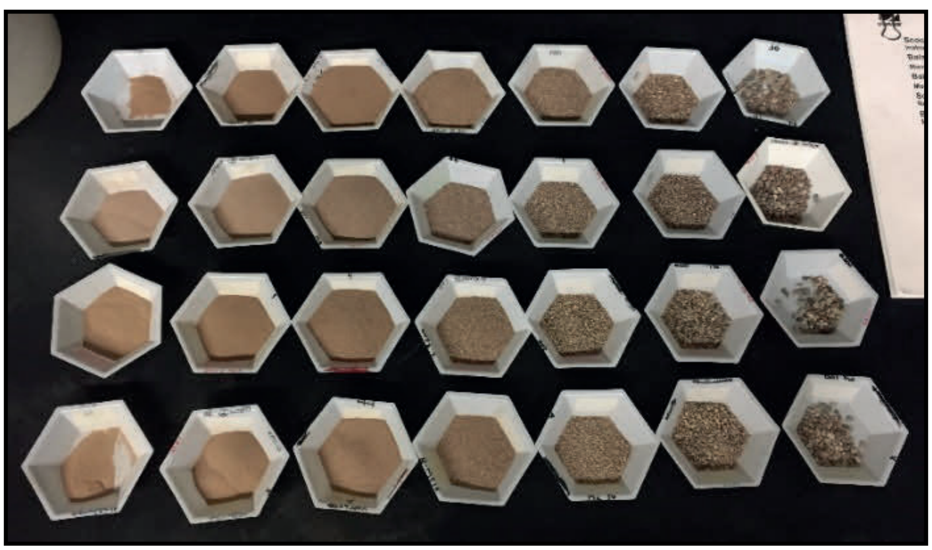


Figure 39: The three soil types (A, B, and E) and the original adobe were sieved and placed on weighing boats. Source: Declet 2017.

- **Combined Dry and Wet Sieving**

In addition to the typical sieving method, Combined Dry and Wet Sieving was also performed following ASTM D422, with the use of a dispersion agent, 4% sodium hexametaphosphate (HMP) (40g/L) and deionized water. It is typical of fine particles to agglomerate and adhere to coarser particles, which occurred in the particle distribution (sieving) test. HMP prevents particles from flocculating during the particle size determination test. A viscous material is semifluid in consistency due to internal friction. When added to scattered particles in suspension, there is a reduction in viscosity due to the neutralization of the forces of attraction.

Figure 40: Combined wet/ dry sieving procedure. Source: Declet 2017.

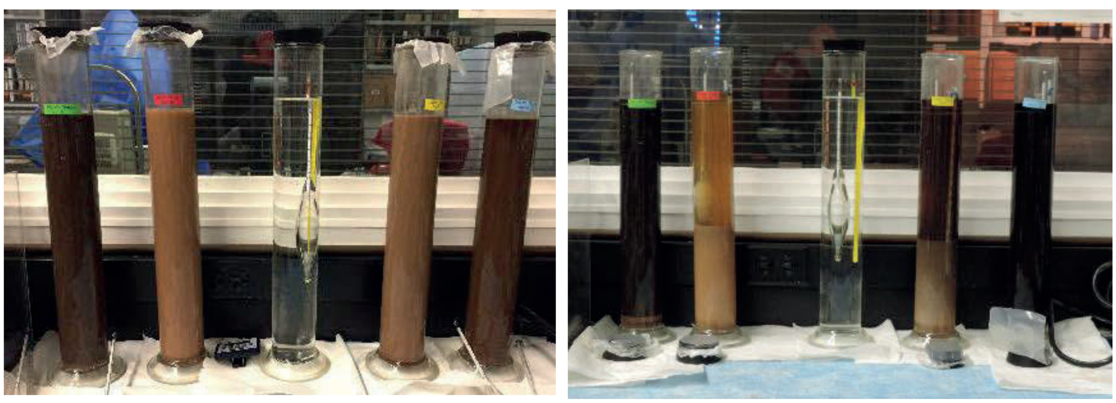


Figure 41: Before and after of the soil sedimentation. Source: Declet 2017.

- **Plastic limit, Liquid limit, and Plasticity Index of soil**

The Plastic and Liquid limits are used to characterize and classify soils based on the relationship between the soil and water content. The test followed ASTM 4318. The properties of clay depend on the amount of water present. The higher the water content, the more the soil flows as a liquid. As the water content decreases, the soil becomes a sticky paste, described as plastic.

The plasticity index indicates a clay's strength when subject to changing soil conditions. Both the liquid limit and the plastic limit show the relative consistency or liquid index. The liquid limit of soils increases when the soil is subjected to constant wetting and drying cycles. The amount of increase indicates a measure of the soil's susceptibility to weathering.

Figure 42: Plastic limit process (left) of rolling soil into a thin 3mm thread. The liquid limit test (right) was also tested using the Casagrande device. Source: Declet 2017.

- **pH of Soil-Acid Solubility**

The soil pH is measured depending on its acidity and alkalinity. By measuring the concentration of hydrogen ions and the material's activity, the pH indicates the solubility of soil minerals and the mobility of ions within the soil. Following ASTM D4972-13, the measurement of the pH was done in both a water solution and a calcium chloride solution, and made use of a potentiometer for more accurate results.

Figure 43: After an hour of combining the soil and the solutions, pH readings were taken. Source: Declet 2017.

- **Organic Content Analysis**

The organic content is expressed as a percentage of the mass of the soil's organic matter to the mass of the dry soil solids. ASTM D2874-14 was used as the standard. It is used to determine the organic matter, the moisture content and any ash content present. Soil structure, water retention capacity, compressibility and shear strength are some properties influenced by the organic content in a given soil. Typically, organic material can be added to accelerate the drying process, to control cracking or to increase the formulation's tensile strength. For these reasons, a substantial amount of organic matter is in some cases beneficial.

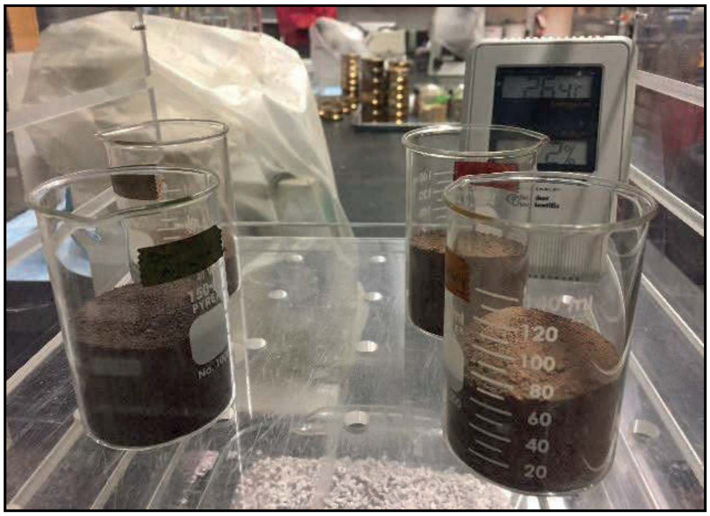



Figure 44: The total organic content was calculated by subtracting the second and first weight loss. Source: Declet 2017.

- **Semi-quantitative Salt Analysis**

The presence of soluble salts in the grout could introduce damaging salts into the adherends that could later crystallize and damage the plaster and adobe. Semi-quantitative Merck strips were used to detect the presence of soluble salts such as chloride (Cl-), nitrate ($NO_3$-) and sulfate ($SO_4^2$).

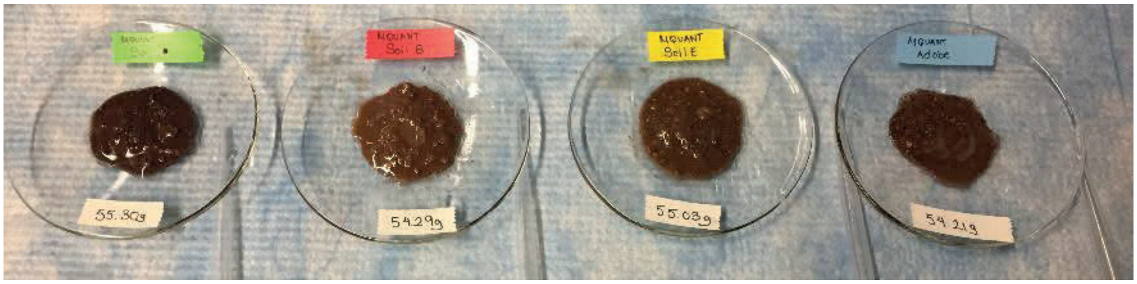



Figure 45: Using a dropper, a few drops of deionized water were dropped over a small amount of soil. This mix was later stirred, and the Merck strip was placed in the solution. Source: Declet 2017.

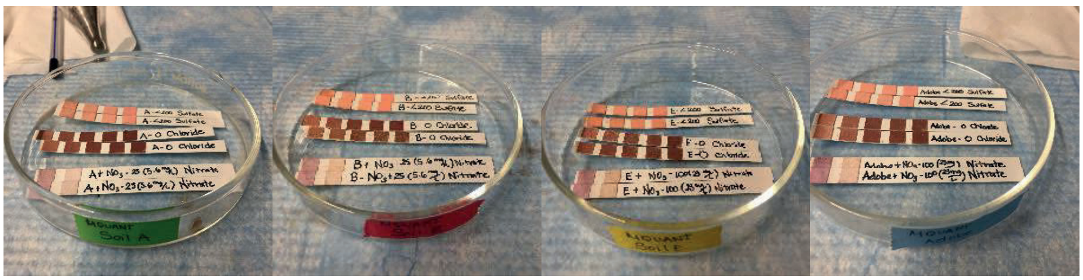


Figure 46: Using a dropper, a few drops of deionized water were dropped over a small amount of soil. This mix was later stirred, and the Merck strip was placed in the solution. Source: Declet 2017.

- **Methylene Blue Adsorption test**

Most clays found in soils are stable, others are swelling and expansive. The original spot test is based on AFNOR NF P 94-068-1998 and ASTM C1777, but for this procedure, Iyer's adaptation for soil grouts was employed (Iyer 2014, 57). To detect the presence of these clays and quantify the cation exchange and ionic absorption capacity of the soils, increasing amounts of Methylene blue trihydrate were added to a liquid soil solution (Türköz and Tosum 2010, 1782). This test determines the amount of methylene blue necessary to cover the surface area of clay particles in the soil.

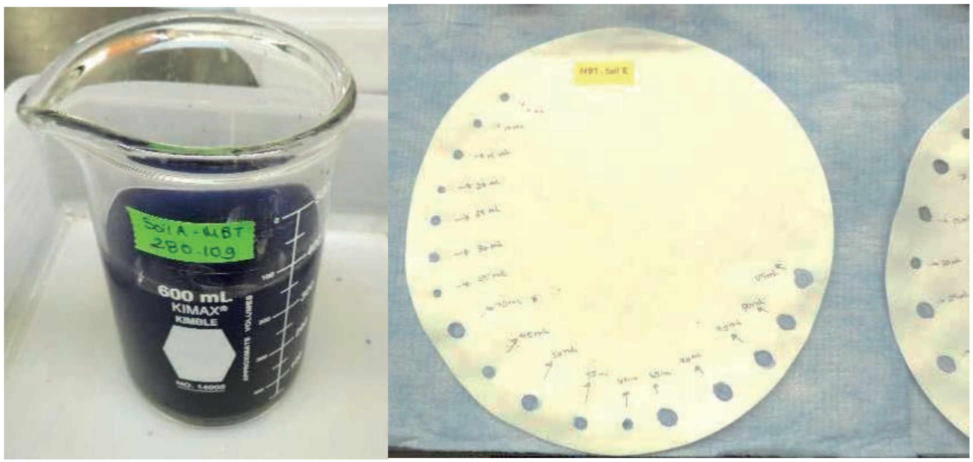



Figure 47: After preparing the 10g/L methylene blue solution, 5ml doses of methylene blue trihydrate were added and with a glass rod, a drop is placed onto filter paper.

### 4.2.1 Summary of Results

- **Particle Size Distribution**

The soil gradation results were grouped into coarse sand, medium sand, fine sand and fines (silts and clays).[58] The results show all three soils were similar in grain size distribution.[59]

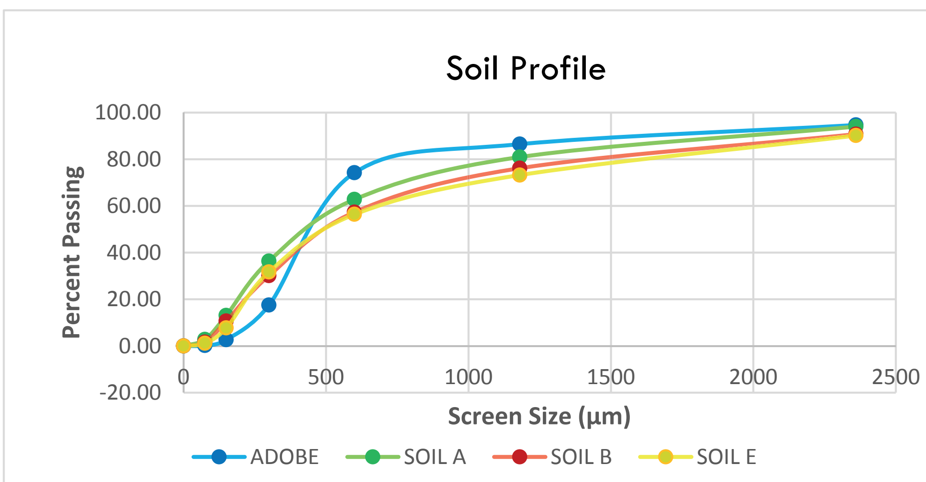



Table 3: Soil Profile for Soil Types and Original Adobe. Source: Declet 2017.

---

[58] Sand particles between 0.02 mm and 2 mm (20 microns and 2000 microns) indicate the clay will have less porosity, increasing its compressive strength.

[59] Soil A has the largest amount of fine sand (49.71%) and silt and clay (13.07%).Soil B follows with 46.69% fine sand and 10.64% silt and clay Soil E possesses 48.68% fine sand and 7.71% clay and silt.

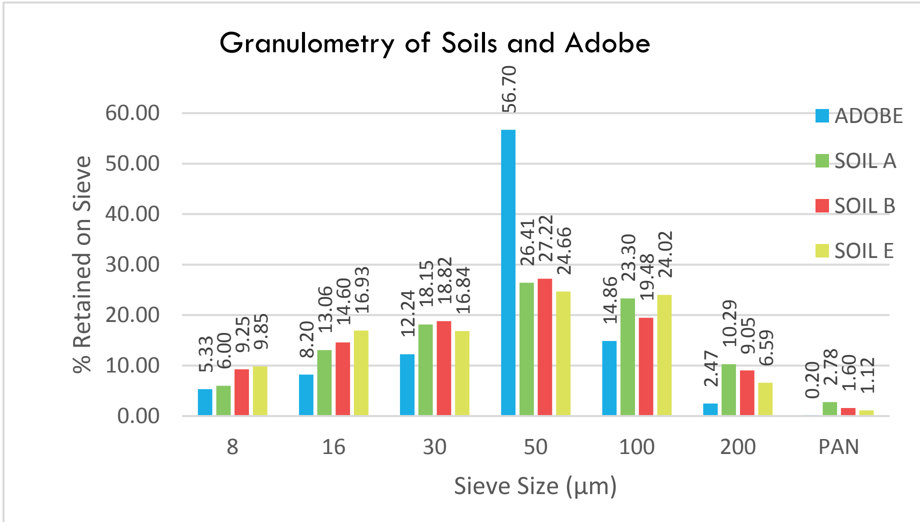



Table 4: Granulometry of soil types and original adobe. Source: Declet 2017.

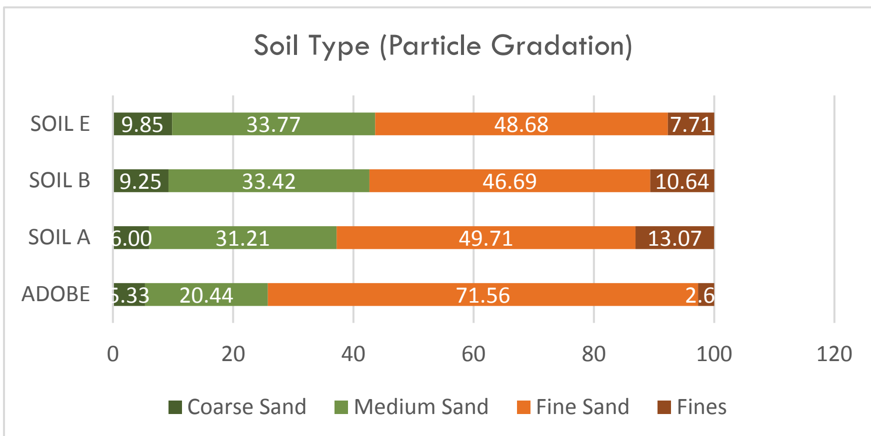



Table 5: Particle Gradation. Source: Declet 2017.

Soil B- Sieve No.8, 5x magnification

Soil A- Sieve No.30, 5x magnification

Soil E- Sieve No.30, 10x magnification

Figure 48: Fine particles attached to the coarse particles of the soil types. Source: Declet 2017.

- **Combined Dry and Wet Sieving**

The Combined dry/wet sieving test required the use of a dispersing agent (sodium hexametaphosphate) which help disperse the particles, which once fully dried, were sieved.[60] The results for the "Dry Sieving" portion of the combined dry/wet sieving show Soil B had the largest amount of fine sand and fines, followed by Soil A and Soil E.

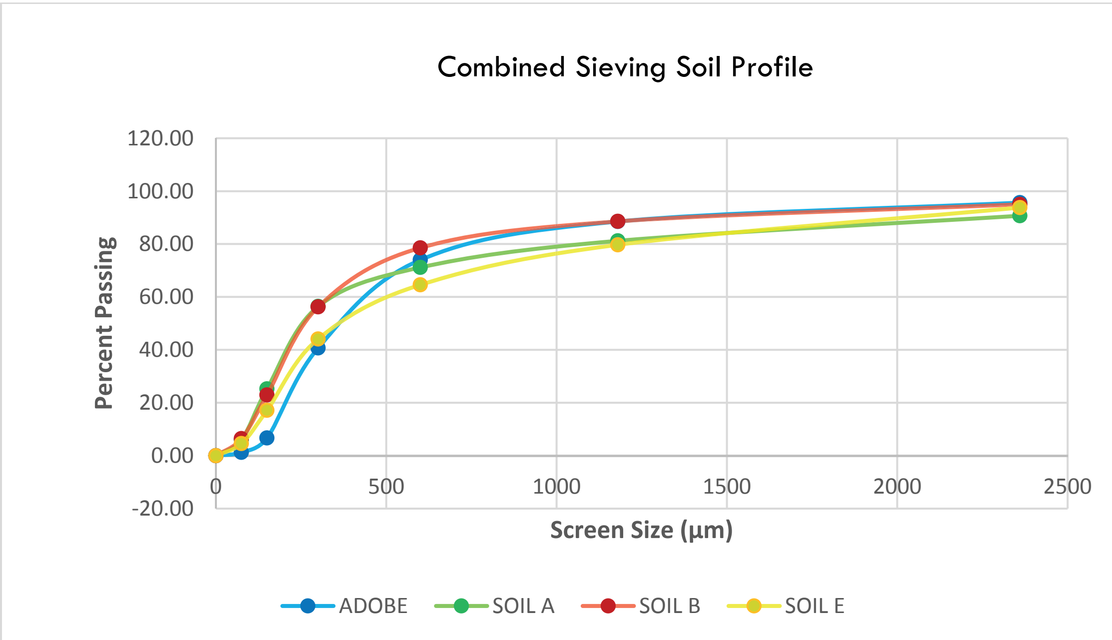



Table 6: Combined Dry Sieving Soil Profile. Source: Declet 2017.

[60] The results show Soil B has the largest amount of Fine sand (55.61%) and Fines (22.95%) which would be better for the grout. Soil A follows with 45.94% Fine Sand and 25.22% Fines. Soil E is last with 47.43% Fine Sand and 17.16% Fine Sand.

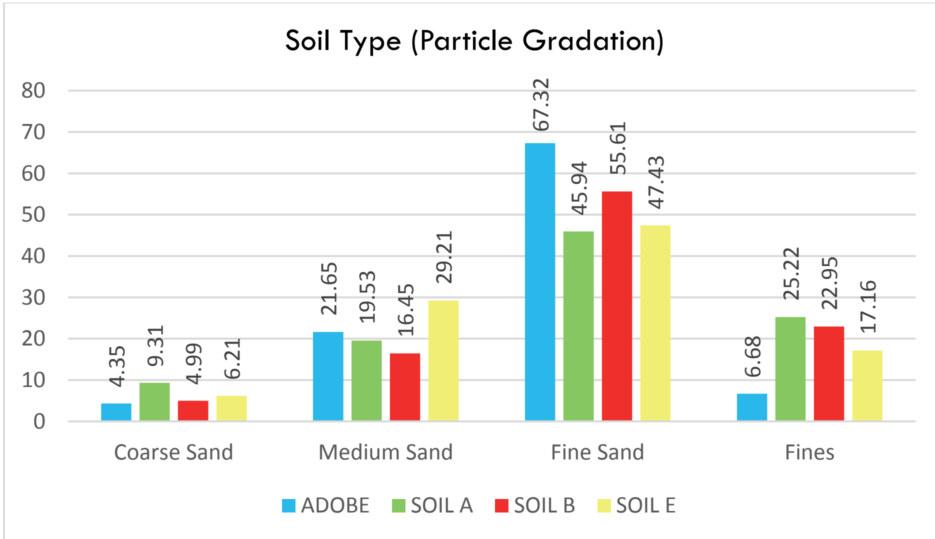



Table 7: Combined Dry Sieving Particle Gradation for soil types and original adobe. Source: Declet 2017.

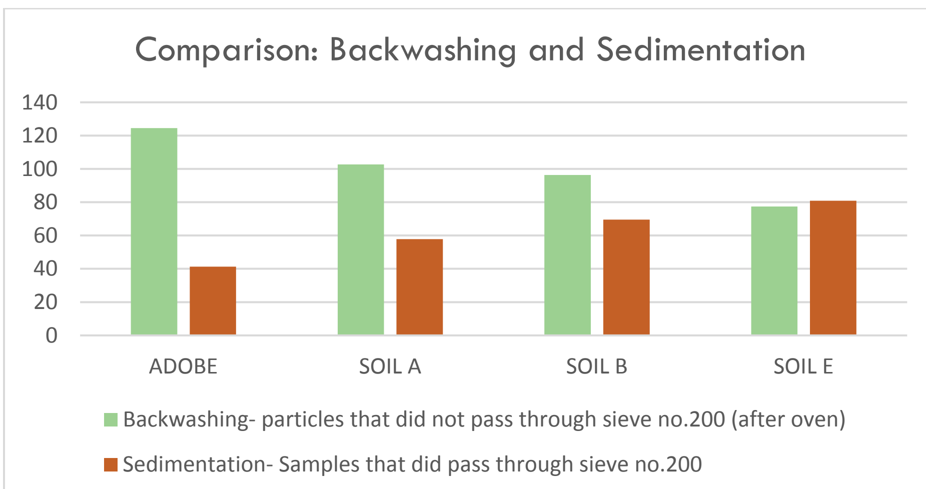



Table 8: Source: Amount of particles that did and didn't pass through Sieve no.200. Declet 2017.

The specific gravity of the suspension (of the particles that pass through sieve no.200) is based on Stokes Law, which states that the terminal velocity is proportional to the square of the particle diameter. Larger particles in suspension will settle quicker than smaller particles. Therefore, the longer the smaller fines take to settle, the higher the hydrometer reading. Soil E started with the highest number, and has settled at a slightly different rate. See Appendix B for overall results.

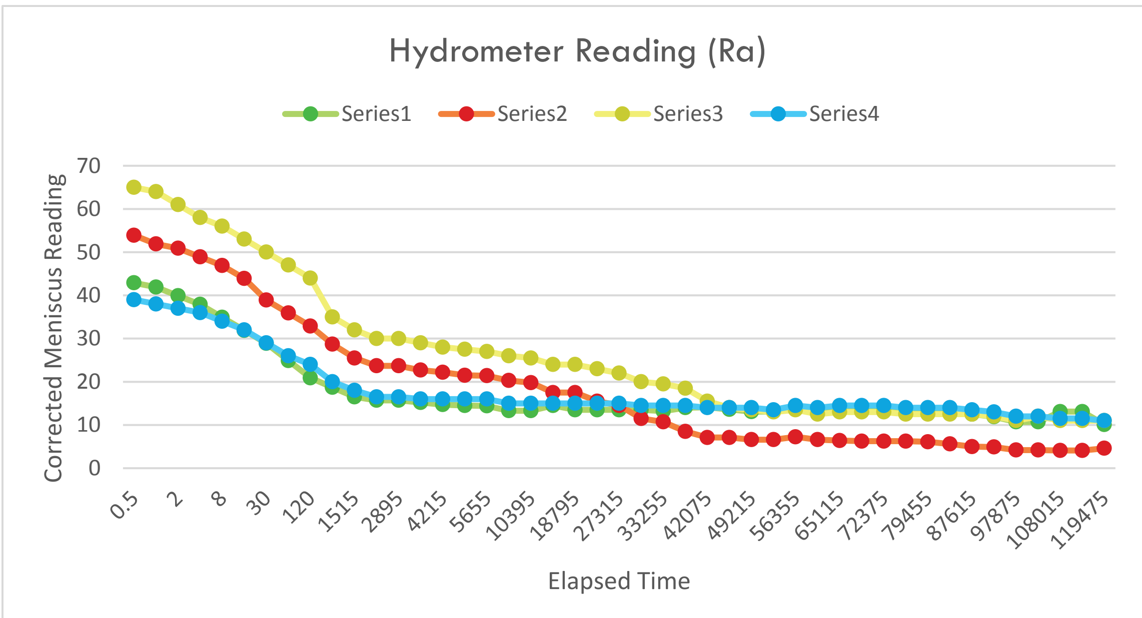



Table 9: Hydrometer Readings for soil types and original adobe. Series 1: Soil A, Series 2: Soil B, Series C: Soil E, and Series 4: Original Adobe. Source: Declet 2017.

- **Plastic limit, Liquid limit, and plasticity index of soil**

Any optimal grout, and especially soil-based grouts, should not display excessive shrinkage. A soil with a high amount of clay increases chances of shrinkage and cracking. For these reasons, the selected soil must have a balanced ratio of clay, silt and sand. Grouts with a reduced amount of clay need less water to achieve fluidity.

The Plasticity Index relies on the amount of clay present in the soil, indicating the fineness of the soil and its capacity to change form without altering its volume. A high Plasticity index indicates an excess of clay or colloids, which may become too expansive. Soils with a low Plasticity Index are very sensitive to changing soil mass, meaning that a very small amount of water will cause the soil to change from a semi-solid to liquid form. Soils with a plasticity index near 16% have the best compaction characteristics, meaning the moisture content in the soils allows it to be compacted with the least effort. All of the soils tested had a plasticity index ranging from 14 to 17.

The soils tested did not have a high plasticity index. Soil E had the highest plasticity index out of the soils tested with Soil B following closely behind. Soil A had a plasticity between 11 and 16, indicative of clay loam (medium plasticity).[61] Soil B had a plasticity index of 14 to 18, also characteristic of a clay loam (medium plasticity). Soil E had a higher plasticity index of 16 to 19 but still falls under the category of a clay loam (medium plasticity). However, the original adobe sample proved to have very low plasticity, characteristic of a high sand and silt content with very little clay.

Soil E also had a higher liquid limit than the rest of the soils, followed by Soil B. In terms of the soil's activity, which is calculated taking the ratio of the PI to the percentage of smaller clay particles, all of the soils were less than 0.75, meaning the clay in these soils is inactive. The coefficient of activity means that the clay has a small volume change,

[61] The soils fall under USC group CL, a fine grained soil described as inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.

suitable for grout formulation. Typical values of inactive soils are: Kaolinite: Activity of 0.3-0.5, similar to the adobe soil (0.31); Halloysite (hydrated): Activity of 0.1-0.2 similar to Soil A (0.25), Soil B (0.21) and Soil E (0.21).

Compressibility is based on the liquid limit of soils that are mostly composed of silt and clay. Soil A has a 29-30 LL (low compressibility), Soil B has a 29-33 LL (low/medium compressibility), and Soil E has a 32-36 LL (medium compressibility).

As seen in the Graph for Soil Plasticity, soils above line A are inorganic clays of low, medium, or high plasticity. While soils below line A are inorganic soils of varying compressibility, organic silts and clays. Since the adobe tested from Tumacacori has a plasticity index lower than 10 and a liquid limit lower than 23%, this soil is termed

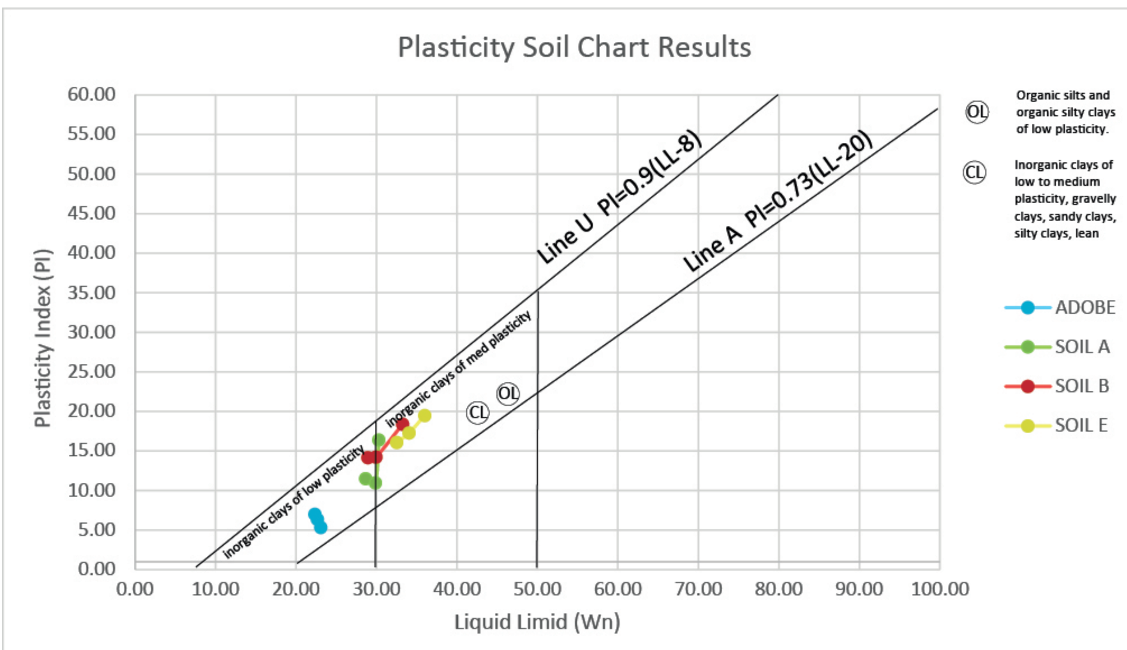



Table 10: Plasticity soil results for soil types and original adobe. Source: Declet 2017.

cohesionless. On the contrary, the soils tested for the grout have a plasticity index higher than 10% and a 30% LL. This makes them well suited for grout.

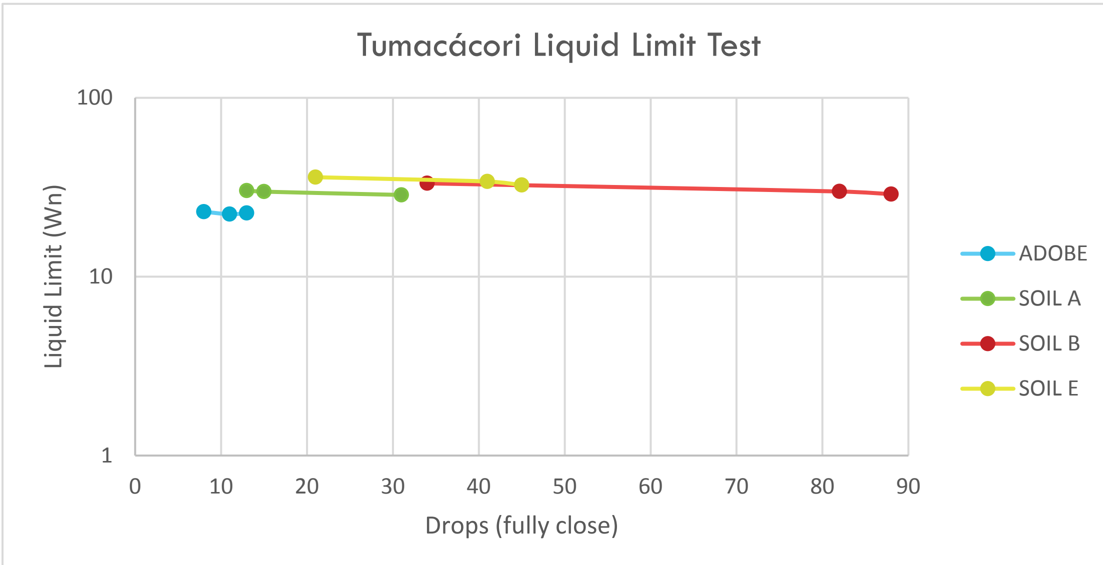



Table 11: Liquid Limit Test for soil types and original adobe. Source: Declet 2017.

- **pH of Soil-Acid Solubility**

Soil B (8.84) and Soil E (8.71) are strongly alkaline while Soil A (8.31) is slightly alkaline. The high pH can affect the stability of clay minerals since it can lead to the formation of stable clay minerals in suspension. On the contrary, a low pH can promote clay flocculation. All the soils scored close to each other, so no definite selection was made based on this test.

| **Samples** | **pH reading Soil+Water** | Temperature Soil+Water (°C) | **pH reading Soil+Calcium Chloride** | Temperature Soil+Calcium Chloride (°C) |
|---|---|---|---|---|
| ADOBE | **7.8** | 16.3 | **6.25** | 16.6 |
| SOIL A | **8.31** | 16.3 | **6.4** | 16.3 |
| SOIL B | **8.84** | 16.3 | **6.78** | 16.4 |
| SOIL E | **8.71** | 16.3 | **6.83** | 16.5 |

Table 12: Soil pH results. Source: Declet 2017.

- **Organic Content Analysis**

Soil E had the highest organic content with a 5.16%, which is beneficial for grout formulation since it can prevent formation of micro cracks within the grout. Soil A and B followed with a weight loss of around 2.6%.

| Samples | Sample Weight before oven (g) | Sample Weight after 110°C (g) | Sample Weight after 220°C (g) | Total Weight Loss in percent | % Weight Loss from Water and CO2 | % Weight Loss from Organic Material |
|---|---|---|---|---|---|---|
| ADOBE | 73.55 | 72.56 | 72.15 | 3.25 | 1.35 | **1.90** |
| SOIL A | 103.09 | 101.13 | 100.33 | 4.58 | 1.90 | **2.68** |
| SOIL B | 104.35 | 102.51 | 101.7 | 4.30 | 1.76 | **2.54** |
| SOIL E | 103.78 | 99.19 | 98.43 | 9.58 | 4.42 | **5.16** |

Table 13: Organic Content Results. Source: Declet 2017.

- **Semi-quantitative Salt Analysis**

All three soils possessed very low chloride, nitrate, and sulfate content.

| Samples | Chloride Cl- | Nitrate $NO_3$- | Sulfate $SO_4^2$- |
|---|---|---|---|
| ADOBE | 0 mg/L (LOW) | + 50 mg/L (LOW-MED) | <200 mg/L (LOW) |
| SOIL A | 0 mg/L (LOW) | + 25 mg/L (LOW) | <200 mg/L (LOW) |
| SOIL B | 0 mg/L (LOW) | + 25 mg/L (LOW) | <200 mg/L (LOW) |
| SOIL E | 0 mg/L (LOW) | + 50 mg/L (LOW-MED) | <200 mg/L (LOW) |

Table 14: Semi quantitative salt analysis results. Source: Declet 2017.

- **Methylene Blue Adsorption test**

All of the soils had similar results. Soil B displayed a slight blue halo after 95 ml of the methylene blue tryhydrate solution. Soil A reacted after the addition of an 80 ml solution, followed by Soil E with 75 ml and the original adobe with 70 ml. The light blue halo was very difficult to observe throughout all of the samples.

### 4.2.2 Original Adobe Results Conclusion

Past analysis of the original adobe described the soil as fine grain and having low plasticity (6) (O'Bannon 1978, 13-15).[62] It has been described as poor in clay size with large amounts of sand and silt (Brown et al. 1979, 31). Others agree with the soil's low shrink-swell potential, such as Chambers who concluded the plasticity index was 5 (Physical Science Technician 1978, 7). This corresponds with the plasticity index found for the original adobe, an average of 6, characteristic of a sand or silt soil with very little clay. Due that the Adobe soil tested from Tumacácori has a plasticity index lower than 10 and a liquid limit lower than 23%, this soil is a cohesionless. The percentage of fine particles was also found to be extremely small in comparison to the soil types characterized. The original adobe has a 7.8 pH reading, a very low amount of organic material, and only contained 50 mg/L of nitrates.

[62] Historic analysis of original adobe is found on Section 2.1.3.

## Chapter 5: Grout Design

In order to ensure the soil grouts displayed optimal grout performance, specific properties and performance characteristics were tested. These include working properties (wet grout) such as flow and viscosity, wet density, shrinkage and expansion and bleeding; properties during setting and curing and hardened properties such as capillary water absorption, water retention, water vapor transmission permeability, and splitting tensile strength.

| Desired Properties for Grout | | |
|---|---|---|
| Wet | Good injectability | Working |
| Wet | Low viscosity/ good fluidity | Working |
| Wet | Good penetration | Working |
| During Setting | No bleeding | Working |
| During Setting | Reasonable setting time | Working |
| During Setting | Low toxicity | Working |
| During Setting | Setting ability in humid environment | Working |
| During Setting | Minimal shrinkage | Performance |
| Dry | Good workability | Working |
| Dry | Low content of soluble salts | Performance |
| Dry | Compressive strength (similar or less than substrate) | Performance |
| Dry | Adhesion strength (shear strength) (similar or less than substrate) | Performance |
| Dry | Good water vapor permeability | Performance |
| Dry | Low density | Performance |
| Dry | Low water absorption | Performance |
| Dry | Sufficient water retention | Performance |

Table 15: Required properties for a successful grout. Source: Declet 2017.

### 5.1 Selection of Soil "E" for grout binder

Out of the soils tested (A, B and E), soil E was selected. No definite selection was made based on the soil pH test, The Semi-quantitative Salt Test and the Methylene Blue Test results all scored close to one another. In addition, a substantial amount of fine particles were agglomerated and attached to the coarser particles in all the sieves for all the soils. For this reason, these readings are misleading and were discarded.

A high clay content in the mix often leads to higher flexural and compressive strength. A grout mix with too much clay may lead to more shrinkage, swelling, poor fluidity, but good binding. Although Soil E has the highest plasticity index and liquid limit values, it falls under the clay loam category (medium plasticity). The higher the liquid limit of the soil, the higher the plasticity and compressibility of soils.[63]

| Material Characterization Testing | Standard/ Reference | Results |
|---|---|---|
| **Particle (grain) size distribution** | ASTM C136-06 | Soil A has the largest amount of fine sand and silt and clay, followed by Soil B and Soil E. **Results were discarded in favor of combined wet dry sieving**, since fine particles were agglomerated to the coarse particles upon higher magnification. |
| **Plastic Limit, Liquid limit, and plasticity index of soil** | ASTM 4318 | **Soil E had the highest plasticity index and liquid limit** out of the soils tested (**but not excessively high**) with Soil B following closely behind. Coefficient of soil activity was below 0.75, indicating the soils are inactive. |
| **Combined dry/wet sieving** | ASTM D422; ASTM D1140; Nityaa Iyer 2014 (P.36) | **Soil B had largest amount of fines**, closely followed by Soil E. Soil A had a very small amount. The original adobe also had a very low amount of fines. |
| **pH of Soil-Acid Solubility** | ASTM D4972-13 | All the soils scored close to each other, so **no definite selection** was made based on this test. |
| **Organic Content Analysis** | ASTM D2974-14 | **Soil E had the highest organic content**, which is beneficial for grout formulation since it can prevent formation of micro cracks within the grout. |
| **Semi-Quantitative Salt Analysis** | Merck Strips | All three soils **possessed very low** chloride, nitrate, and sulfate content. **No definite selection** was based on this test. |
| **Methyl blue adsorption test** | AFNOR NF D 94-068-1998; Nityaa Iyer 2014 (p.57) | All the soils scored similar results, so **no definite selection** was made based on this test. |

Table 16: Overview of results for characterization of soil types and original adobe. Source: Declet 2017.

Soil E stood out in the “Sedimentation” portion of the combined wet/dry sieving test that measures the amount of finer particles (desirable for the grout). Soil E also had the

63 Throughout the plastic limit test, Soil E was rolled 8 continuous times without crumbling, taking a larger amount of water without crumbling. Soil A on the other hand, only reached 2 rolls before crumbling. Soil A was eliminated first due to its low plastic and liquid limit result. It did not contain enough clay, proving hard to roll and crumbling during the plastic limit test.

highest organic content with a 5.16%, which is beneficial for grout formulation since it prevents formation of micro cracks within the grout.

### 5.1.1 Grout Formulation and Components

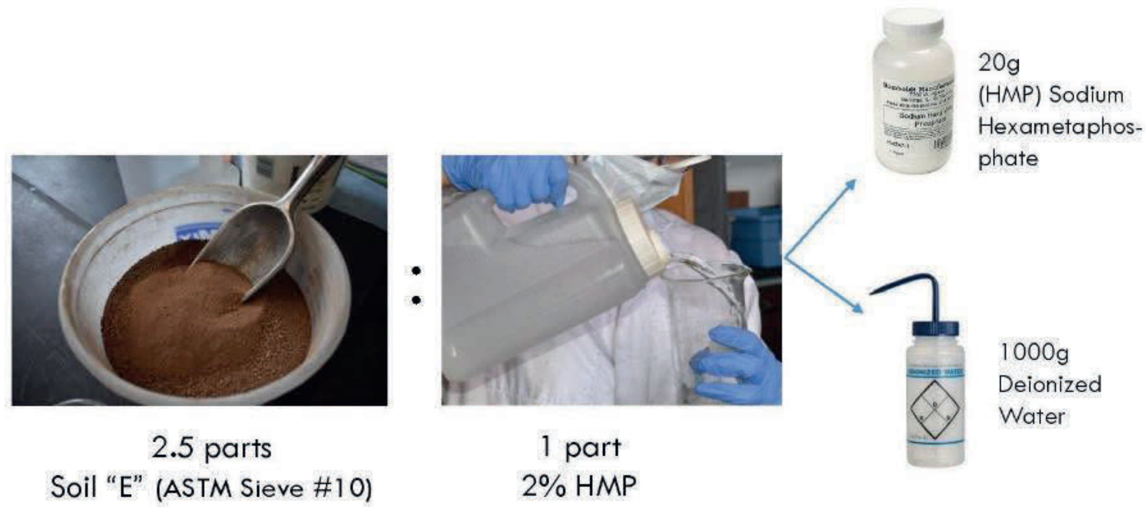



Figure 49: Components of the grout: 2.5 Soil E: 1 part HMP. Source: (Right Images) Declet 2017 (Left Images) DMW 2016; Humboldt Manufacturing.

The formula used for the grout was 2.5 parts soil to 1 part water with 2% sodium hexametaphosphate. The 2.5:1 ratio is based on Iyer's research on soil grout formulations for earthen structures. After subjecting several formulations of the grout to numerous tests that characterized the grout's rheology and shrinkage, Iyer concluded a 2.5:1 solid to liquid ratio (by volume) performed the best. 2.5:1 soil to 2% sodium hexametaphosphate fared better than the soil to water alone. In some instances, the samples prepared with this ratio showed signs of cracking in the qualitative drying shrinkage test.[64]

[64] Higher ratios such as 3:1 proved to be too viscous and complicated to pour and so Iyer discarded these from her testing early on.

Soil “E” for the grout was sieved through a #10 ASTM sieve (2mm particle size). Typically, grouts for structural repair are sieved through a #8 sieve (2.36 mm particle size) based on the assumed width of the cracks and the diameter of the cannula to be used. But for reattachment of the lime plaster to the substrate, a smaller particle size is preferred given the crack and detachment dimensions. The use of a #10 ASTM sieve eliminates large sand particles, producing a finer and more diluted grout while reducing micro cracking due to drying shrinkage (Vargas et al. 2008; Silva et al. 2012).

Sodium Hexametaphosphate (HMP) was used as an amendment to increase fluidity without increasing the amount of water used. The 2% HMP solution acts as a deffloculant, dispersing clay particles and ensuring uniform separation amongst the particles. HMP prevents flocculation, known as suspended matter that combines into large aggregates big enough for gravity to accelerate their settling. Adding HMP improves fluidity and reduces shrinkage and viscosity (Lourenco et al. 2013).

### 5.2 Grout Mixing

As mentioned in the previous section, the selected recipe for the grout was 2.5 parts soil sieved through #10: 1 part 2% HMP solution. A five gallon bucket was used as the mixing bucket to make larger quantities of the grout.[65] The quantities required for the sand and soil were first calculated prior to mixing. 20% more than the minimum requirement for each testing was made to account for any grout retained on the container. The ingredients were mixed with the use of a Milwaukee hand held corded 3/8

[65] Around 2.5 gallons of the bucket was used to make one batch.

electric drill with a speed range of 0-850 rpm. A metal 5 gallon spiral paint mixer was attached to drill to mix the grout for 4-5 minutes. A timer was set each time, and at the 3 minute mark the bucket was scrapped before continuing to mix. A total of 9 batches were made on 5 separate days to complete all the grout testing.

Since the soil was moist inside its container, around 900 mL of the soil was placed on a glass dish and was left in the oven to dry at 40°C for 16 hours to remove some of the moisture. It was later placed in the desiccator for 1 to 2 hours before sieving through #10 sieve. The sodium hexametaphosphate solution was prepared 500 mL at a time. Per every 500 mL of deionized water, 10 mL of $Na_6P_6O_{18}$ in solid powder form was added to get a 2% HMP solution. Deionized water was used to prepare the HMP solution in order to prevent any introduction of salts, impurities or any alteration of pH that might come from tap water.

## 5.3 Grout Testing

| Sample Schedule | | | | |
|---|---|---|---|---|
| | Test | Standard | Shape | Size |
| Wet Grout Testing | Flow/ Viscosity | **ASTM C939;** ASTM C230; ASTM C780; DIN 18555; **Nityaa Iyer 2014 (p.69)** | Funnel | Orifice diameter of 4.76mm (less than 1/4") at 50 mm long (around 2") |
| | Wet Density | ASTM C937; ASTM D4016 and CRD C-78; **Bicer-Simsir and Rainer 2011 (p.21)** | Cylindrical cup | 400 ± 1 mL cup; 88 mm depth |
| | Drying Shrinkage Test (qualitative- saucers and prisms) | Ferragni 1984; **Nityaa Iyer 2014 (p.74-79, 92-93)** | Prism | 1" x 1" x 6-3/4" |
| | Expansion & Bleeding | **ASTM C940C;** EN 447:1996; **Bicer-Simsir and Rainer 2011 (p.18)** | Glass cylinder | 500 mL cylinder 25mL cylinder |
| Dry Grout Testing | Capillary water absorption* | NORMAL 11/85; Zajadacz and Simon 2006; **Bicer-Simsir and Rainer 2011 (p.35)** | PVC pipe | 4" high tube, 1" diameter |
| | Water retention | **RILEM 11-6;** ASTM C1506; DIN 18555, part 7; Zajadacz and Simon 2006; **Bicer-Simsir and Rainer 2011 (p.51)** | / | 200 mL |
| | Permeability (water vapor transmission) | **ASTM E96/ E96M-15; Bicer-Simsir and Rainer 2011 (p.40)** | Circular disk | 2" diameter 1" height |
| | Splitting Tensile Strength | ASTM D3967, ASTM C348-72; ASTM C496 M-11 (splitting tensile test) EN 196-1; Ferragni 1984, **Bicer-Simsir 2009; Bicer-Simsir and Rainer 2011 (p.28); Nityaa Iyer 2014 (p.77)** | PVC pipe | 2" hollow pipe; 4" height |
| Mock-up | Shear Bond Strength (adhesion) | **ASTM D 905,** BS EN 196-1; Bicer-Simsir and Rainer 2011 (p.62) | Square | 3.5" X 3.5" X 1" Plaster 3.5" X 3.5" X 3" Adobe 0.25"-0.50" Grout Thickness |

Table 17: Testing schedule for grout testing. Source: Declet 2017.

### 5.3.1 Wet Properties

- **Flow/ Viscosity**

This test method was performed to determine the time of efflux for a known quantity of grout to flow through standardized flow cone funnel. It is to be tested on grouts with fine aggregates smaller than 2.36mm. The rate of the grout is then compared to the rate of water flowing through the same assembly. Values obtained are not direct viscosity measurements, but the test helps to characterize the rate of flow of the designed grout. The test is based on ASTM C939, and Iyer's 2014 adaptation for mud grouts.

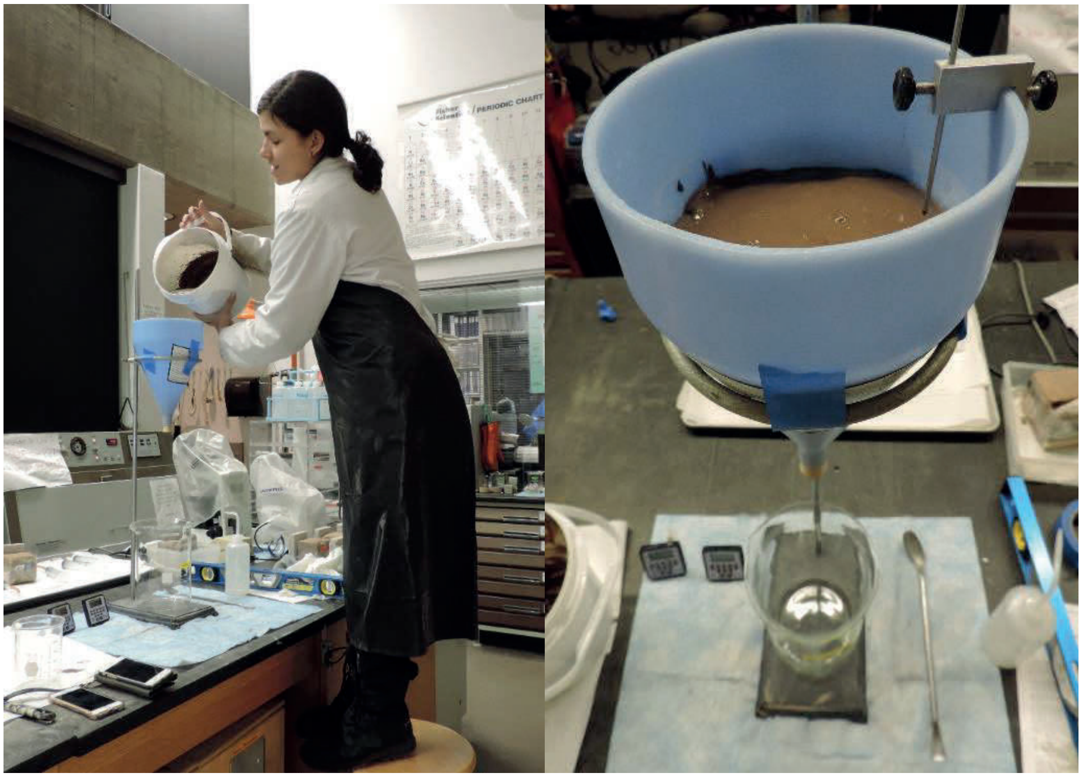


Figure 50: First, 1725 mL of water was poured through the cone twice and two flow measurements were recorded. Afterwards, the prepared grout was poured, and three stop watches were started once the finger stopper was removed. Source: Declet 2017.

- **Wet Density**

The aim of this test is to determine the density of the wet grout. Two similar methods were used to test the grout, GCI's Laboratory Testing Procedure and Field Testing Procedure. In the former, a 400 mL container is filled with grout and weighed, while in the latter a syringe is filled with grout and weighed.

The test follows GCI’s Section *2.3 and 4.5 Wet Density* test for grouts, as well as ASTM C185. However, GCI’s standards did not call for the compaction of the grout since grouts are less viscous than mortars and a tamper can cause air entrapment. Two batches were done for both methods, but the procedure is essentially the same. The containers were weighed and later slowly filled with the grout. The tamper was only used to tap the sides. For the cylindrical metal container, the top was made flush with a trowel. Afterwards, the cup was weighed again. Similarly, the syringe was filled with 12 mL of grout instead of 5 mL, and was tapped to remove any air bubbles. It was finally weighed to calculate the wet density of the grout.


Figure 51: The syringe was filled with 12 mL of grout instead of 5 mL, and was tapped to remove any air bubbles. It was finally weighed to calculate the wet density of the grout. Source: Declet 2017.

- **Drying Shrinkage**

The grout shrinkage was evaluated using two tests, a visual qualitative method and a quantitative test measuring the drying shrinkage of grout prisms. The former consisted of visually identifying shrinkage on a grout sample poured on a terra cotta saucer for a period of 28 days. Grout shrinkage was identified by visible surface cracking and diameter change. The aim of the quantitative prism test is to measure the decrease in length of the prisms under controlled drying conditions. However, many other factors influence the material's dimensional change in the actual assembly, such as restraint, ambient temperature, and humidity.

For the visual qualitative method, the grout mix was poured into four terra cotta saucers within a minute of mixing. This test method is based on Washa (1966, 190) and Iyer's 2014 adaptation.

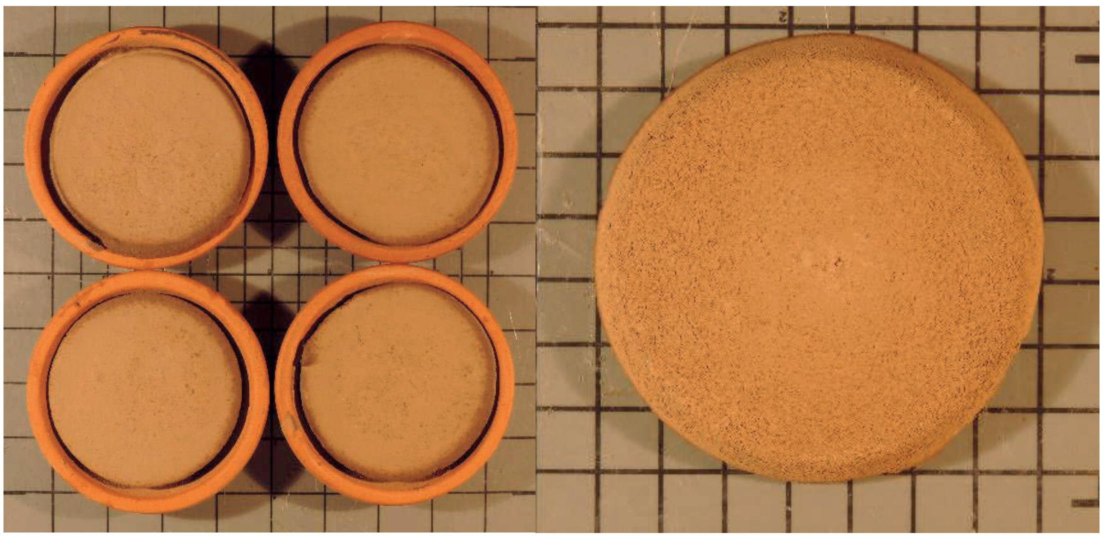


Figure 52: These were observed for 28 days, while monitoring the temperature and relative humidity. Source: Declet 2017.

The drying shrinkage prism method followed ASTM C1148-92A and ASTM C490.[66] From one mold, 3 prism samples could be made, each measuring up to 1 in x1 in x 6.75 in.[67] According to ASTM, the specimens are to be removed from the mold 72 hours after being poured. However, that standard is for masonry mortar. The samples were left in the container for an additional 24 hours to let them set properly.[68]

---

[66] A minimum of five specimens were required for this test. The effective gage length was that of 5.25 in.
[67] The molds had been previously prepared by Nityaa Iyer in 2014.
[68] The length of the prisms was measured after 4, 11, 18 and 25 days of air drying using a length comparator device.

The gauge studs attached to each end of the specimen are carefully placed in the device to obtain a length reading, and record length change for the specified period. The minimum reading of the dial was recorded when rotation of the sample occurred. The specimen was always measured from the same end.

Figure 53: The molds were pre lubricated several times with mineral oil to prevent the wooden mold from drawing water out of the grout. After pouring, the molds were observed to make sure no sagging occurred. The total percent shrinkage of the specimens was calculated at the end. Source: Declet 2017.

- **Expansion & Bleeding**

The amount of expansion and bleeding characteristics of the soil grout were analyzed by measuring the total change of volume and accumulation of bleed water in a tight sealed cylinder for a certain period of time. A desirable grout should not visibly segregate or bleed after being prepared. Otherwise, it might clog while being injected in the assembly. A suggested bleeding percentage for a grout should be less than 0.4%.

The test follows GCI's Section *2.2 Expansion and Bleeding* test for grouts, as well as ASTM C940-16. The GCI's reference mostly follows the ASTM procedure, with the exception of the grout volume. Instead of the original 800 mL used to test concrete, 400 mL was used to test grouts. The ambient temperature of the room should be at 23°C to run the test. The temperature of the grout should also be collected, and it should be at 23°C +/- 2°C.

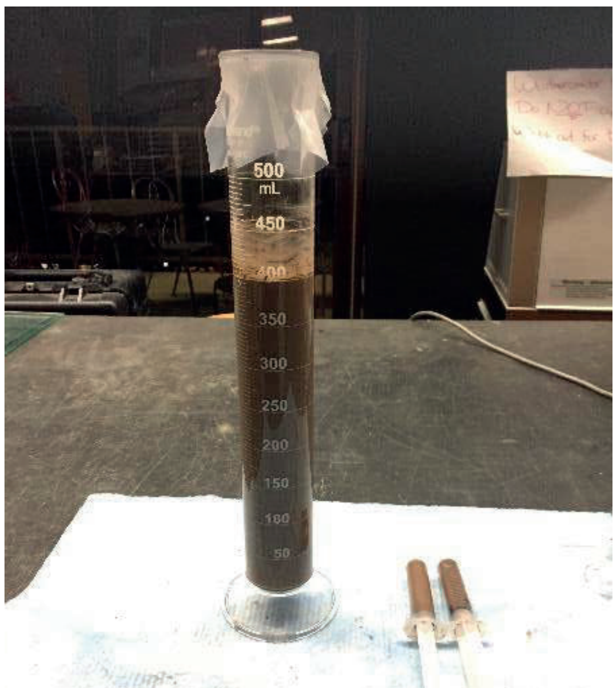



Figure 54: After mixing, the grout was poured into a 500 mL graduated cylinder until the sample reached 400 mL. The top was covered with parafilm to prevent evaporation of any possible bleeding water. Source: Declet 2017.

### 5.3.2 Hardened Properties

- **Splitting Tensile Strength**

The tensile strength of the tested grout should be equal to or less than the original plaster and adobe substrate to prevent damage to the original fabric. The grout is more likely to fail due to tensile stresses rather than shear stresses, and even less so in compressive strength. Consequently, the cylindrical sample will most likely fail as a response to horizontal tension forces, rather than vertical compression forces, which ultimately leads to failure in the center of the specimen. This tensile strength obtained through this test, however, is expected to be 10% to 50% higher than direct tensile strength measurements. The universal mechanical testing machine used must match the description found in ASTM D3967-16, or any equipment capable of compressive loading.

Grout cylinders were prepared 28 days prior to testing to allow for enough curing time. Rather than preparing the specimens according to the GCI's 2.5 Splitting Tensile Strength procedure, which requires the use of an injectability apparatus using the sand column test, the earthen grout was prepared by pouring directly into pvc molds, 4 inches in length and 2 inches in diameter. ASTM C 496/C 496M was used as a reference document to the GCI's grout manual specifications. An additional 2 inches was taped to the upper length of the cylindrical pvc mold to account for any slumping of the grout. Right after pouring, the molds were lightly hit against the surface 10 times to allow any air bubbles to exit the surface.

The specimens were allowed to initially cure for 7 days before removing the upper section that was taped. In addition, one of the molds was take out to study the curing process of the grout column. However, the column sagged, and so the rest were left in the molds to cure for an additional two weeks before removing the mold all together. Conversely, hydraulic lime based grouts and other cements are required to be covered with plastic sheeting prior to testing. The specimens were oven dried two days before testing to ensure uniform drying. Two wooden strips were then taped to both the top and bottom sides of the samples in order to apply the load evenly. Prior to testing, the diameter and length were measured three times to reach an average to the nearest 0.01 in.

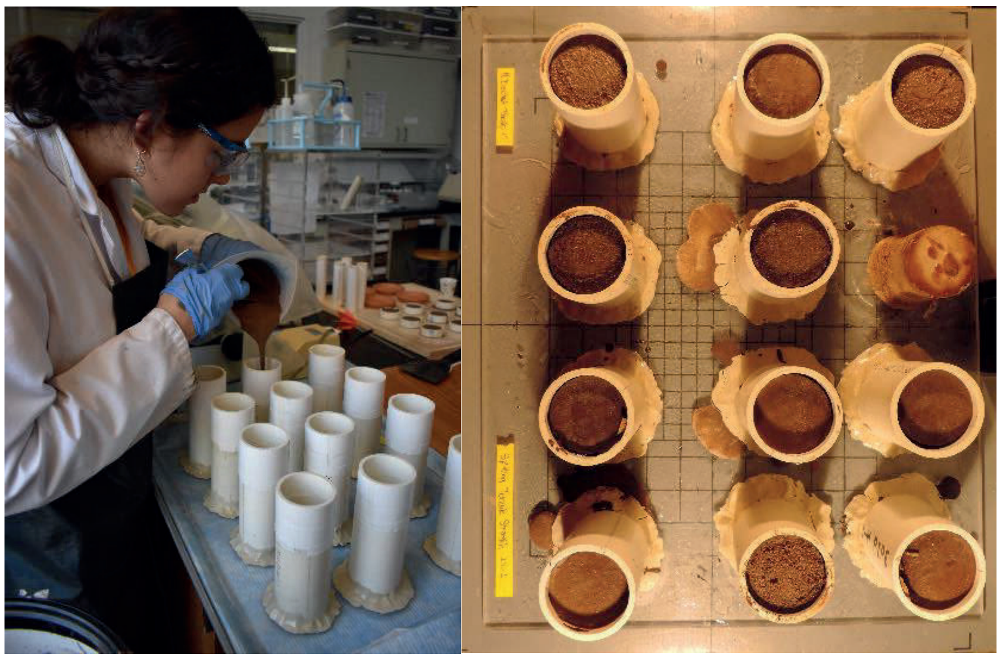


Figure 55: The earthen grout was prepared by pouring directly into pvc molds, 4 inches in length and 2 inches in diameter. Source: Declet 2017.

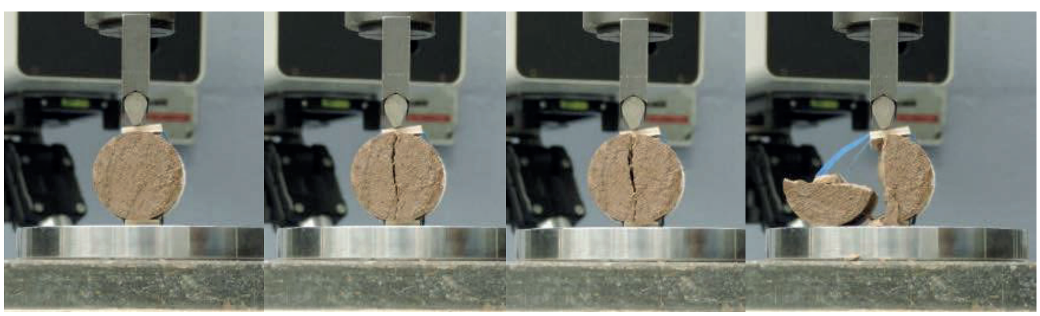


Figure 56: The maximum load, also known as the breaking load was recorded in psi to calculate the splitting tensile strength. Source: Declet 2017.

- **Capillary water absorption**

The aim of the test is to estimate water absorption behavior on hardened grout using the gravimetric method. An empty transparent plastic tube, measuring 4.5 in by

1.625 in, was filled with the grout using a syringe with a catheter tip while the tube is geld vertically. After curing, the grout columns are placed in a water filled container and the weight change of the specimen is recorded for a defined period of time.

The test follows GCI's Section *2.7 and 4.8 Capillary Water Absorption* test for grouts, which are based from NORMAL 11/85 and RILEM test.II.6. A clear linear fluorescent Tube Guard, was cut using a bandsaw to make at least three specimens. All columns were stored for a minimum of two weeks before removing from container. After removal, samples were dried in an oven at 40°C for 24 hours, until the difference between two successive measurements was less than or equal to 0.1% of the weight of the sample. The column's length and diameter were measured using a digital caliper.

A tray with a perforated metal stand was filled with deionized water until reaching 2mm above the stand. The glass tray was placed inside a larger container with a petri dish filled with desiccant to prevent condensation. The column was then placed on a stand and the amount of water absorbed was recorded periodically following standard procedures. The lid was placed on the plastic box to minimize evaporation and to control the RH.

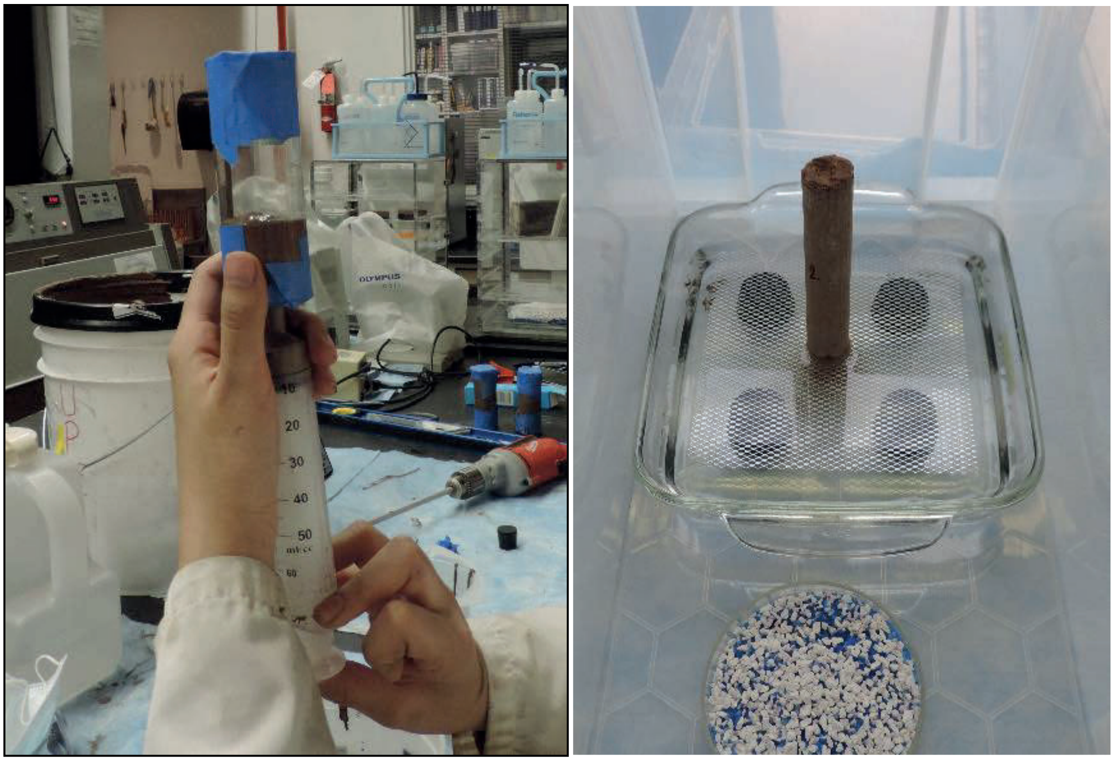


Figure 57: All columns were stored for a minimum of two weeks before removing from container. The glass tray was placed inside a larger container with a petri dish filled with desiccant to prevent condensation. Source: Declet 2017.

- **Water retention**[69]

The following test aims to determine the water retention value of the grout when subjected to suction. The suction portion recreates the absorption mechanism that occurs amongst the building materials. The test is usually for hydraulic cement based mortars and plasters, however this test can also be used on nonhydraulic injection grouts. The grout's ability to retain water also provides insight regarding the grout's injectability and flow. The water retention value, WRV, is computed from the water loss that occurs between the original grout and the grout after being subjected to suction. A higher water

---

[69] The water retention apparatus, a filtration assembly, was built for the use of this thesis by John Hinchman, HSPV Penn lecturer and research specialist for the ACL, with assistance from Courtney Magill, HPSV lab manager and recent program graduate.

retention capacity indicates the grout's strong resistance to having its water absorbed by the substrate which will allow the grout to flow a greater distance.

The test was mostly based on GCI's Section 3*.2 Water Retention and Release* test for grouts. ASTM C1506-16b and RILEM TC 116-PCD were used as reference standards. However the GCI's reference for grouts does not calculate the WRV using flow calculations, as required in the ASTM. The change was made to accommodate grouts, since the flow table is designed for mortars and plaster which have a higher viscosity than grouts. The perforated dish was also not filled to the top edge and the total volume of the grout was reduced to 200 ml to ease transportation in order to record the weight of the assembly, as well as limit the amount of material lost in the process. For this particular assembly, the perforated brash dish was replaced with a pa perforated plexiglass dish. The brass funnel was also replaced with a zinc plated galvanized funnel. The glass stopcock, vented Erlenmeyer armed flask vacuum pump, vacuum regulator closely match the ASTM description.

The filtration assembly consists of a grout mix collected in a perforated dish that rests on a funnel that is connected by a three way stopcock to a vacuum flask, to which a controlled vacuum is applied. First, a 2.5 µm filter paper, 150 mm diameter is wetted and placed on the perforated dish, and is weighed to the nearest 0.01g. After preparing the grout mix, 200 ml of the solution is poured into a beaker which is then poured into the perforated dish. If the grout has a thicker consistency, a non-absorptive tamper is used to tamp across the surface 15 times. Afterwards, the assembly is once again weighed. The rim of the funnel is then greased with Vaseline and the perforated dish containing the grout is placed at the top. The stopcock should be closed at this point.

Once the vacuum is adjusted to 2.4$\pm$2 kPa, the stopcock is turned (and opened) to apply the vacuum to the funnel, and the stopwatch is started. Once suction is applied for 120 seconds, the stopcock is turned again to expose the funnel to atmospheric pressure. The dish is then removed from the funnel, and the underside of the dish is dabbed with a damp cloth. Finally, the dish is weighed. The test is performed twice.

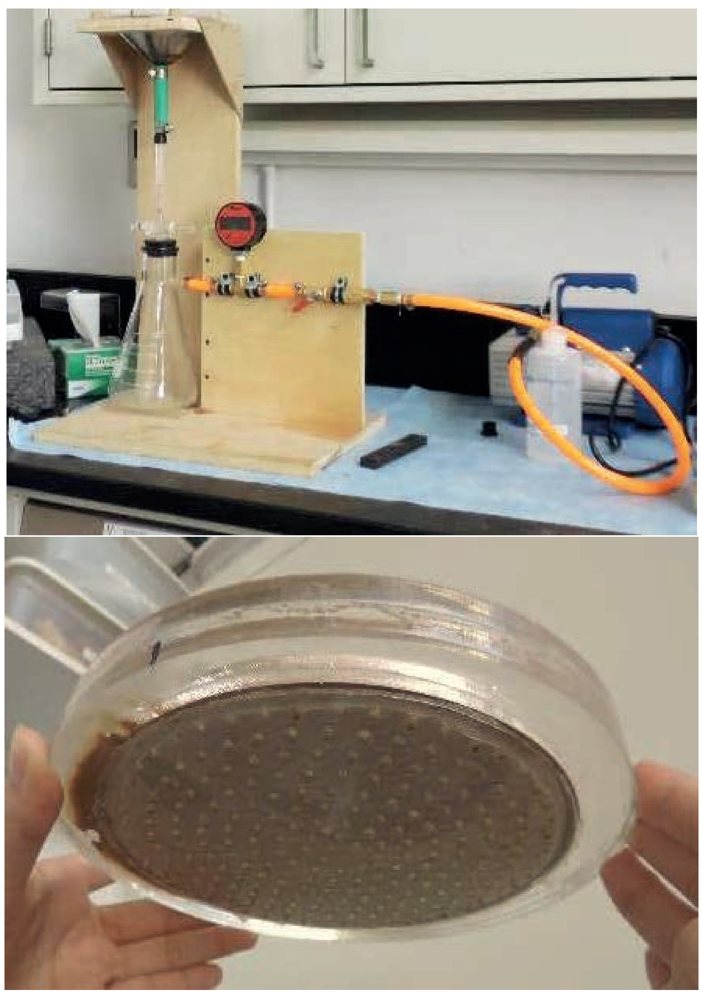


Figure 58: After performing the test, the underside of the dish is dabbed with a damp cloth. Source: Declet 2017.

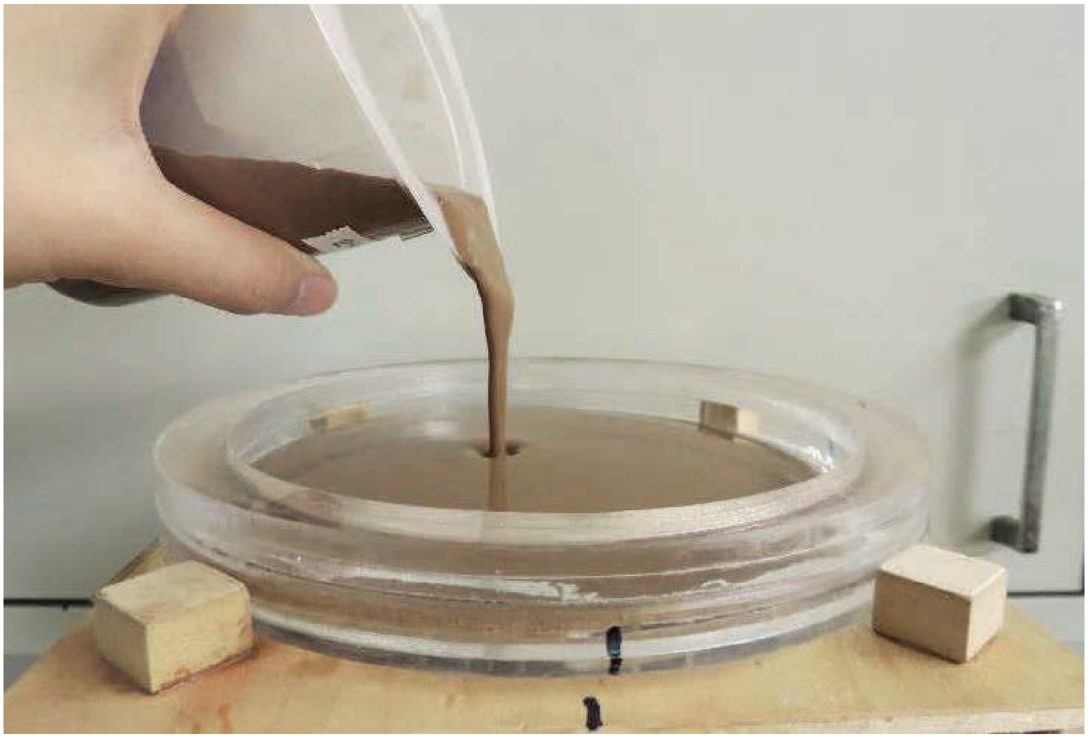


Figure 59: After preparing the grout mix, 200 ml of the solution is poured into a beaker which is then poured into the perforated dish. Source: Declet 2017.

**Adaptations:** With the stopcock closed, the pressurewas adjusted to 2.4 kPa, instead of 7 kPa (53 mm Hg). To maintain the vacuum at a constant rate, the suction was applied for a total of 120 seconds, instead of 60 seconds. For the first 60 seconds, the vacuum should achieve a constant reading. The suction is let to run for an additional 60 seconds at that constant rate before closing the stopcock.

- **Permeability (WPT)**

The vapor permeability of the grout was determined by measuring the rate of water vapor transmission. Water vapor permeability is the time rate of water vapor transmission through a unit area of a flat specimen of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions. Water absorption is different from water transmission since the former is a process where the water goes through the pores of the materials and is retained without transmission. The desiccant method was used for the measurement of permeance.[70]

Figure 60: The grout was first mixed and poured into pvc disk molds, 2 inches in dimeter and 1 inch tall. Source: Declet 2017.

[70] In such method, the specimens is sealed against a tri-cornered beaker filled with water. The assembly is placed in a controlled atmosphere, and the assemblies are weighed periodically to measure the rate of water vapor movement through the specimen and into the desiccant.

Figure 61: In order to achieve a tight seal between the grout disk and beaker, paraffin was melted on a hot plate and was dropped alongside the rim of the beaker with a dropper. Once finished, the test assembly was weighed. Source: Declet 2017.

The aim of the test is to measure the values of water vapor transfer through permeable and semipermeable materials, which helps determine the permeability of porous building materials. Properties such as vapor transmission are key to understand moisture management and durability of building materials. The test closely follows ASTM E96/E96M-15 and the desiccant method.[71]

[71] To activate the desiccator's desiccant, a single layer of new desiccant and color indicative blue spheres were oven dried at 400°C for an hour, and were let cool before being placed inside the desiccator.

### 5.4 Mockup Assembly (plaster + grout + gap + adobe)

Replicated mockup samples were made early on to be tested. To complete the mockup assembly, unstabilized adobe from a commercial manufacturer in New Mexico, Earth Adobes, was used due to its availability, and traditional way of producing the mud bricks. Once the samples were made, the grout was tested in shear bond strength. Lime scratch coats were formulated to be friable and half of the samples were consolidated with Nanolime, following Jang's recent thesis (Jang 2016). The lab samples simulated conditions anticipated in the field conditions and focus on the efficacy of the grout on consolidated and nonconsolidated lime plasters.

The adobe blocks were previously cut with a Felker Mason Mite II® masonry wet saw to fit the dimensions required for the assembly. The large blocks were cut down to 3.5” x 3.5” x 3 blocks. Wood spacers measuring 3.5 inches x 1.5 inches, and 3.5 inches x 1.25 inches were placed under the plaster coupons to create the ½ and ¼ gaps.

Figure 62: Felker Mason Mite II masonry wet saw used to cut the adobe. Source: Declet 2017.


Figure 63: Adobe assemblies measuring 3.5in x 3.5in x 3in. Source: Declet 2017.

### 5.4.1 Plaster Facsimiles

Throughout the course of this research project, two different plaster mix batches were made on two separate occasions using two separate mold designs with the same dimensions: 3.5in x 3.5in x 1in. The first mold was a wooden grid that could make three samples at a time. These were used for the first batch but two samples out of eleven broke during the demolding process, so new molds were made to complement those. The second wooden mold was designed to make the demolding process easier. Preparation of the plaster remained consistent.

Material analysis of the original plaster suggests it is composed of a high-calcium, nonhydraulic lime containing less than 5% magnesium (Highbridge Materials Consulting, Inc., 2014). Following previous plaster characterization descriptions and Jang's facsimile preparation, Type S hydrated lime was used as the binder. Local sand, sieved through ASTM sieve No.8 was used as the aggregate. The local sand closely resembled that of the Tumacácori mission plasters (Jang 2016, 41). The selected formula to recreate the friable plaster found at the mission consisted of 1 part Type S Lime: 5 parts sand: 1.3 parts water. This produced a friability similar to that observed on site.

The ingredients were mixed using a mechanical mixer, Hobart C-100, following ASTM C305-14 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. 24 hours before mixing, all the molds were generously coated with up to eight layers of mineral oil to prevent the wood from absorbing the mix's water. The original grid mold did not have a base, so a plywood sheet with blotting paper was placed underneath the mold.

Figure 64: Friable plaster formulation consisted of 1 part Type S Lime: 5 parts sand: 1.3 parts water.
Source: Declet 2017.

The binder and aggregate were first lightly mixed by hand before adding water. Less than 10% of the total amount of water was added to the bowl before starting the mixer. The mixer was kept at the slower speed for 30 seconds, and was later scraped. The same portion of water was added before beginning the mixer once again. Once the mixer was stopped for a resting period of 3 minutes, the bowl was enclosed to prevent water evaporation. Afterwards, the speed was adjusted to medium, and was kept running for a minute before adding more water. The mixer was stopped and covered once again for 3 minutes, before adding more water and continuing at a medium speed for 3 minutes. This last step was performed twice for the mix to be ready.

| Ingredients | Ratio | Batch 1 **(1/12/17)** | Batch 2 **(1/22/17)** |
|---|---|---|---|
| **Type S Lime** | 1 | 500 mL | 700 mL |
| **Local Sand** | 5 | 2500 mL | 3,500 mL |
| **Water** | 1.3 | 650 mL | 910 mL |
| Total Samples | - | 11 square coupons | 16 square coupons |

Table 18: Plaster coupon ratios. Source: Declet 2017.

The samples were left to cure for a period of 28 days in an indoor controlled environment with an average of 20.5°C and 39.7 % RH. The samples were kept covered for the first week. After 7 days of drying and curing, the samples were demolded.

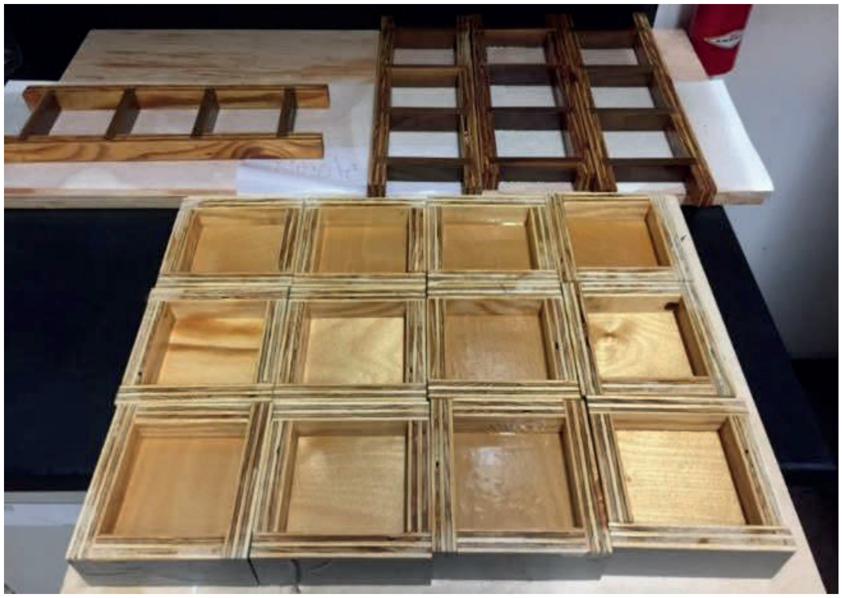


Figure 65: All molds were continuously coated with mineral oil 24 hours before preparing the mix. Source: Declet 2017.

Figure 66: Two 0.5in wood strips were glued onto the bottom of the base (3.5in x 3.5in x 0.75in). The sides consisted of two 3.5in x 2.25in and two 4.875in x 2.25in plywood pieces.. Source: Declet 2017.

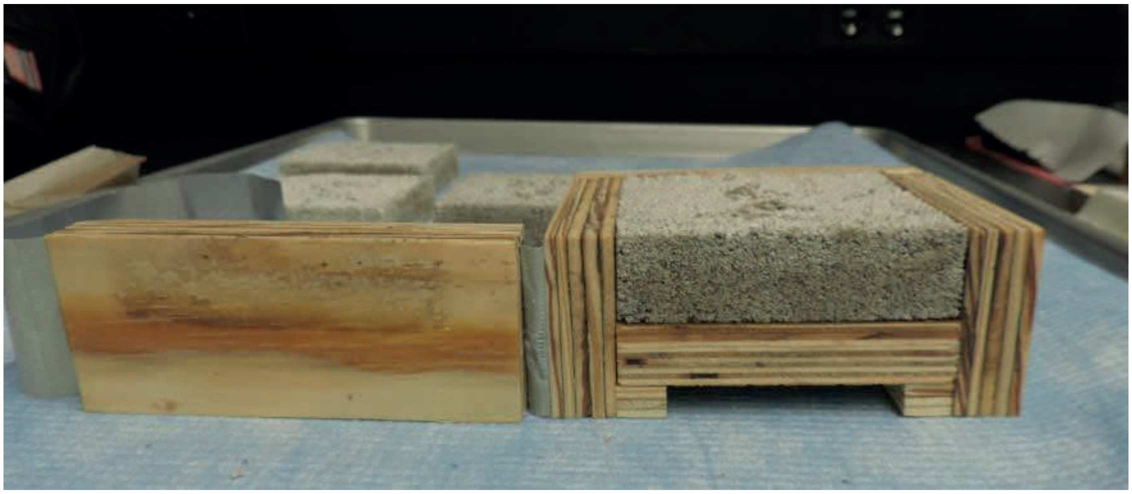


Figure 67: The new molds improved the demolding process. The sides of the mold were attached with masking tape. Source: Declet 2017.

### 5.4.2 Nanolime consolidation on friable plaster facsimiles

As previously mentioned, twelve plaster coupons were consolidated with nanolime. After curing for 28 days, and the samples were placed on a tray with a metal grill. Nanolime is created by combining nanoscale calcium hydroxide particles with alcohol such as ethanol.

Nanolime consolidation, which works through the carbonation process, has demonstrated to improve grain cohesion of friable plaster, as well as increase durability to weathering without affecting the physical properties of the substrate. After application, the alcohol solvent evaporates to enable the carbonation process. Additionally, calcium hydroxide particles and alcohol display a very low viscosity. The effectiveness of the product was determined by Jang based on effectiveness, compatibility, durability and reversibility (Sassoni et al., 2016).

The consolidant was applied in three cycles, using two solvent concentrations of the nanolime product, CaLoSiL® E5 and CaLoSiL® E25. Prior to application, any loose particles were remove from the surface with a one inch brush following Jang's procedure (Jang 2016, 46). The solution was poured in a tri-cornered beaker 50 mL at a time, making sure to coat the top and bottom surfaces of the square coupons. Any excess nanolime, remaining on the surface was blotted.

Figure 68: Nanolime consolidant was applied in three cycles. Source: Declet 2017.

For the first application, 20 mL was used to coat one square. A total of 200 mL of CaLoSiL® E5 was used to coat all the squares. The second coat, applied the following day, used CaLoSiL® E25. Around 12.5 mL was required to coat one square, and a total of 130 mL to coat all squares. The third application made use of the same concentration, and the amount used for one square coupon was less than 10 mL, and tallied up to 110 mL. These were immediately covered after every application using plastic film, and were placed in a large plastic container with two glass dishes filled with water to keep the relative humidity extremely high for the first weeks. The RH was maintained at 91%. Total curing time consisted of 28 days.

### 5.4.3 Shear Bond Strength

A successful grout should have an adhesion or shear strength similar or less than the adobe substrate and plaster. The aim of this test is to assess the grout's shear bond strength within the mockup assembly consisting of the plaster facsimiles, an adobe block, a wooden spacer and the grout. In any instance, the bond failure should occur within the grout or the bond interface where the substrate and grout meet. The original material must not fail. The test is not completely unbiased, as several factors may interfere with the shear strength of the grout.

The test mostly follows GCI's manual of laboratory and field test methods for injection grouts, Section 3.5, which is based on ASTM D905-08 and EN 196-1 Part 1. The friable plaster samples, both consolidated and un-consolidated, were adhered to the New Mexico handmade adobe blocks with the injection grout. The wood spacers were taped to the plaster surface to recreate the ½ and ¼ inch gaps. The surfaces were taped together with clear adhesive tape to maintain visibility and to prevent the grout from adherence.

All surfaces were prewet with deionized water for 5 minutes, and any remaining water was removed with a luer lock tip syringe and a #14 cannula. To inject the grout a catheter tip syringe with a 3.25 in. tube attached to achieve full surface contact with both planes. Assemblies were not moved during or after grouting to limit micro cracking during curing time. Immediately after, the assemblies were covered with a plastic sheet to prevent immediate shrinkage. After a week of curing, the clear adhesive tape used was carefully slit with a xacto knife and was left to cure for another week.

The tape and wooden spacer was removed prior to placing the assembly into the machine. These were set 6mm deep into the holder. Following GCI 3.5 standards, the loading rate increase was of 2400 ± 200 N·s–1 in compression. Simultaneously, the loading was applied at a rate of 5mm (0.20in.)/1min until failure. Once finished, the maximum load was recorded as the breaking load in Newtons, and the grouted area's length and width was measured as well. The average shear bond strength was calculated at the end.


Figure 69: Assemblies prior to grouting. Source: Declet 2017.

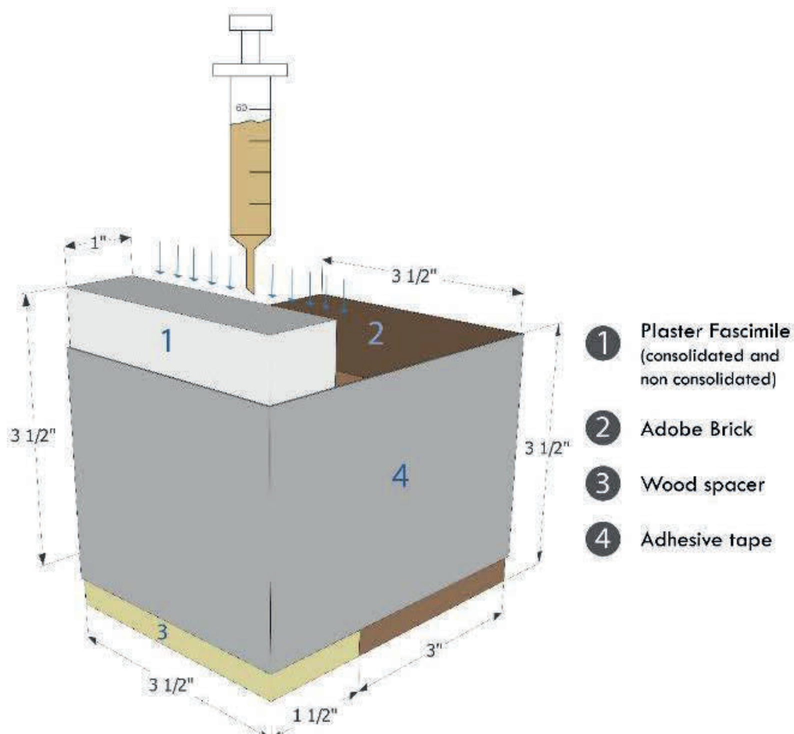



Figure 70: Grout Assembly diagram. Source: Declet 2017.

Figure 71: Adobe faces were pre-wetted prior to the grouting procedure. Grouting was done by attaching a tube unto a catheter tip syringe. Source: Declet 2017.

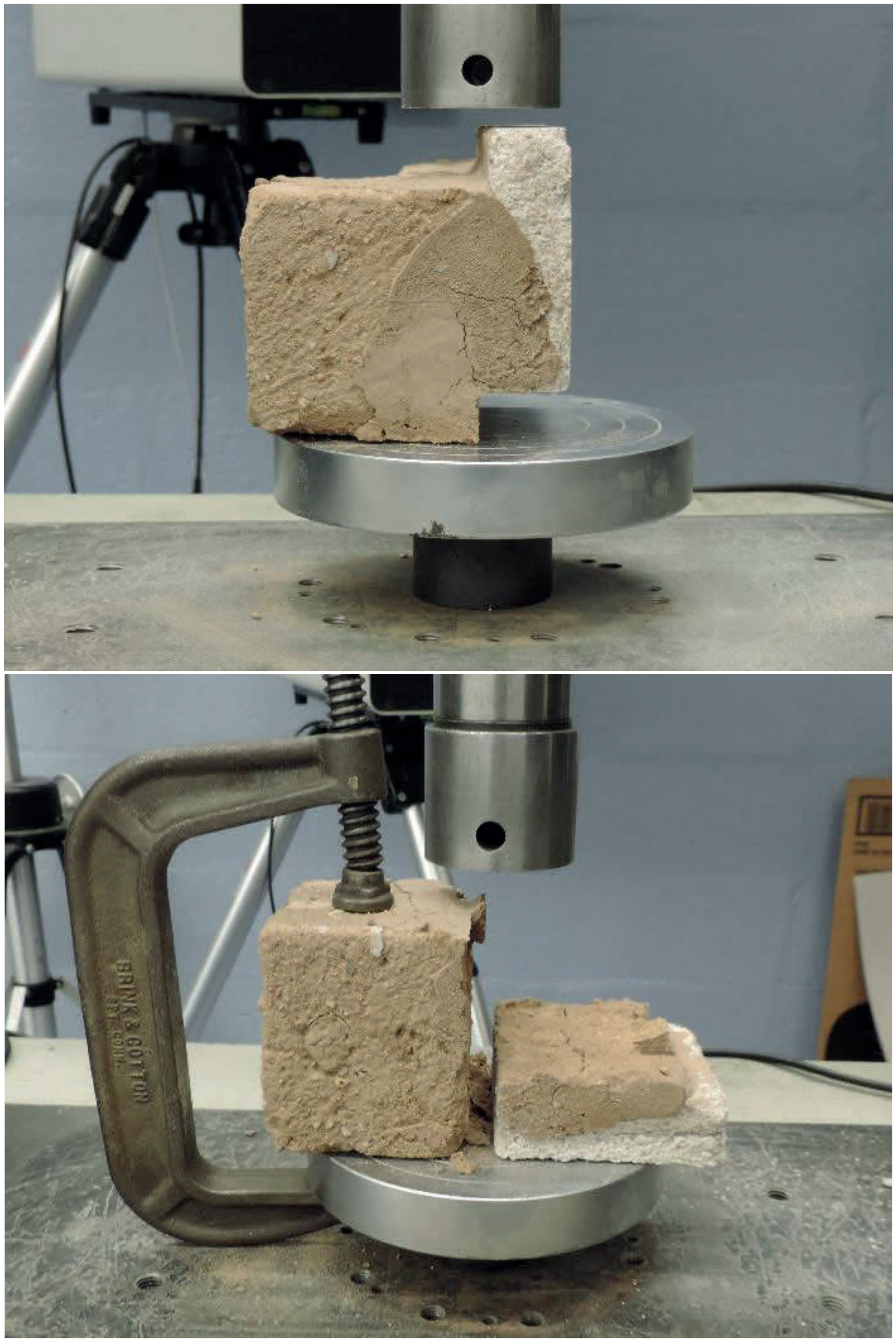


Figure 72: Assemblies before and after testing for shear bond strength. Source: Declet 2017.

# Chapter 6: Laboratory Testing (Rheology)

## 6.1 Flow/ Viscosity

A desirable grout is one with a low viscosity and high flow rate. The higher the Marsh cone viscosity value, the higher the viscosity, while a less viscous fluid will take a longer time to fill the container. The longest time of efflux permitted is 35 seconds. Results are indicated as seconds, and indicate the relative consistency of the fluids.

**Observations:** The amount of the receiving container was typically 20 $\pm$ 5 mL less than 2000 mL due to the fact that the grout residue coated the funnel. Both batches flowed easily, and absolutely no settling of course fraction occurred. For both batches, the grout temperature was between 22°C and 23°C, and the overall temperature in the room was 22.2°C and 18.9°C for the second batch.

| | Marsh Flow Cone Values | | | |
|---|---|---|---|---|
| | Time of efflux of water | | Time of efflux of grout | |
| Batches | #1 | #2 | #1 | #2 |
| Reading #1 (s) | 5.72 | 4.46 | 14.28 | 20.84 |
| Reading #2 (s) | 3.98 | 3.89 | 16.05 | 22.62 |
| Average Reading (s) | 4.85 | 4.175 | **15.165** | **21.73** |

Table 19: Flow and viscosity test results for grout. Source: Declet 2017.

**Results:** Both batches resulted in slightly different times of efflux, yet the readings were 1.8 s apart. In average, the total time of efflux of the grout was 18.02 s, and the total efflux of the water was 4.51 s. In comparison to Iyer's soil grout, this formulation had a higher viscosity than her Sample D (2.5 soil:1 HMP) which averaged 12.88 s (Iyer 2014, 75, 109). Other than sharing the same ratio and use of HMP in water, the soil used by Iyer was different than the one employed here which could explain the different times of efflux.

In comparison to other research on soil grouts, the flow time for the grout prepared by Silva was 34s for 1 cubic decimeter of water, or 34s for 1000 mL of water at 18°C (Silva et al. 2012, 7). Additionally, Silva and Lourenco tested two separate grouts, Mud grout A had a flow time of 85.9 s, and B of 36.5 s.[72] Note that both grout formulations contained HMP in water to improve fluidity.

Grout B is more similar to the Tumacacori designed grout than Grout A, but the components are still very different due to the addition of limestone powder and smaller particle size (2mm).[73] The flow time for Mud B was 35.6s for 1000 mL, displaying a higher viscosity, and less fluidity, than the grout designed for Tumacácori (Lourenco et al. 2013, 5).

### 6.2 Wet Density

**Results:** The grout's wet density was an average of 1.87 g/cc. In terms of compatibility, the grout has a lower density than that of Tumacácori. The density of Tumacácori adobe samples analyzed in 1978 revealed the density to be between 2.46

---

[72] The specimens were left to cure for a period between 27 and 35 days, at a 20°C temperature and 57.5% RH value (Lourenco et al. 2013, 4). Grout A was described as an "artificial" mud grout, 20 Kaolin powder: 80 limestone powder: 0.40 sodium hexametaphosphate. Conversely, Grout B was the "natural" mud grout consisting of 40 parts sieved soil (particle size 0.18 mm- ASTM No.80 sieve), 60 parts limestone powder, and 0.46 parts sodium hexametaphosphate.

[73] The soil used for Grout B had a similar plastic limit to Soil E (16.6% vs 16%), but had a lower liquid limit (23% vs 34.2%), and a lower plasticity index (7% vs 17.6%).

g/cc and 2.56 g/cc (Brown et al. 1979, 35). However, different methods were used to obtain these results.[74]

| TUMA grout | Weight of 12mL syringe (g) | Weight of the grout + syringe (g) | Weight of the grout in syringe (g) | Wet density of grout ($g\times cm^{-3}$) |
|---|---|---|---|---|
| 1 | 4.9 | 27.4 | 22.5 | **1.88** |
| 2 | 6.3 | 29.1 | 22.8 | **1.90** |
| TUMA grout | Weight of the cup (g) | Weight of the grout + cup (g) | Weight of the grout (g) | Wet density of grout ($g\times cm^{-3}$) |
| 1 | 98.63 | 1662.78 | 1564.15 | **1.84** |
| 2 | 101.3 | 1684.25 | 1582.95 | **1.86** |

Table 20: Wet Density Results for grout. Source: Declet 2017.

In comparison, the density for the kaolin and HMP grout tested by Silva's team varied between 1.198 g/cc and 1.347 g/cc, less dense than the grout discussed here.[75] A summary of the grout composition tested by Silva is below:

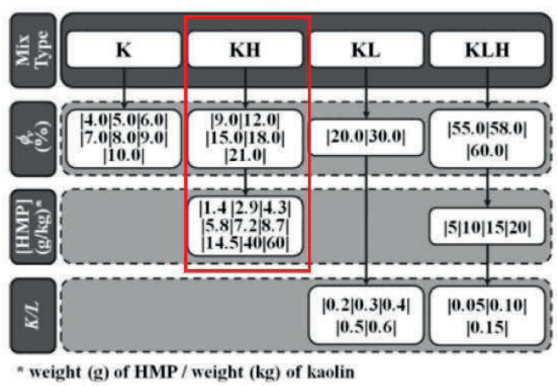


Fig. 3 – Matrix of the tested mixes composition.

Figure 73: Silva et al. grout formulations. Source: Silva et al. "On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion." ISISE, University of Minho, Portugal and Catholic University of Leuven, Belgium, 2012: 29.

74 The first was obtained by calculating the weight change of the wet grout collected in a syringe, while the second was determined by helium pycnometry.

75 These were mixed using a Hobart N50 planetary mixer with a wire whip paddle. The grout was first mixed for 5 min at speed 1, then for 5 min at speed 2, with a 1 min resting period between steps (Silva et al. 2012, 7). The specimens were kept in a controlled environment of 20°C and RH of 65%. Specimens achieved a constant weight in 3 to 5 days.

In comparison to an NHL 3 grout with no additives, the density (volumetric weight) is 0.70 g/cc less than the soil grout designed.[76] However, an NHL grout can expand up to 0.05", more than the soil based grout discussed.

### 6.3 Drying Shrinkage

**Observations (saucers):** The grout placed in the terra cotta saucers performed well. The grout did not crack, but it did shrink uniformly as indicated by a slight gap around the perimeter.

**Observations (prisms):** The specimens were allowed to dry for an additional 24 hours. After 96 hours, the prisms were partially removed from the molds while still attached to the smaller blocks that held the gauge. After two hours, the prims were released and remained attached to the gauge. Both the saucers and the prisms were placed in a controlled environment, 21.5°C average and 50% RH.

| Specimen (prism) | Effective gage length L0 (in.) | 4 days | 11 days | 18 days | 25 days | Drying Shrinkage Average mean | Percent Shrinkage (S) % |
|---|---|---|---|---|---|---|---|
| | | Initial measurement after removal L1 (in.) | Measurement during drying L (in.) | | | | |
| 1 | 5.438 | 7.646 | 5.41 | 5.344 | 5.372 | 5.943 | 41.82 |
| 2 | 5.438 | 6.04 | 4.584 | 4.532 | 4.554 | 4.9275 | 27.33 |
| 3 | 5.438 | 6.478 | 5.096 | 5.062 | 5.068 | 5.426 | 25.93 |
| 4 | 5.438 | 4.786 | 2.632 | 2.59 | 2.618 | 3.1565 | 39.87 |
| 5 | 5.438 | 6.758 | 5.862 | 5.82 | 5.83 | 6.0675 | 17.07 |
| 6 | 5.438 | 9.62 | 8.314 | 8.28 | 8.29 | 8.626 | 24.46 |

Table 21: Drying Shrinkage results for grout prisms. Source: Declet 2017.

[76] Chaux 100 naturelle pure 1 NHL5L 1.5 Sand (well graded sands #6 to #200). Mix is recommended for injection grout by manufacturer, St.Astier.

**Results:** The average percent shrinkage for the six specimens was 29.41% (standard deviation 9.56.) The change in area for the prism specimens was also recorded, averaging up to 3.84%. It is difficult to obtain comparable values with other mud grouts tested by other researchers.[77] Regarding lime grouts, Pingarrón's NHL grout cohort had little or no shrinkage at all after a year cure (Pingarrón 2006, 62).[78]

| Phase Three Formulæ | | | | |
|---|---|---|---|---|
| Proportions (by volume) | | | | |
| Sample | NHL | S | MS | Acrylic in $H_2O$ |
| A | 2.0 | 1.0 | 1.0 | - |
| B | 2.0 | 1.0 | 1.0 | 5% ER |
| C | 2.0 | 1.0 | 1.0 | 10% ER |

| Proportions (by weight in grams) | | | |
|---|---|---|---|
| Sample | NHL | S | MS |
| A | 960 | 525 | 960 |
| B | 960 | 525 | 960 |
| C | 960 | 525 | 960 |
| NHL – St. Astier NHL  S – Sand  MS – Microspheres  Acrylic – El Rey (ER) | | | |

Table 2.4

Figure 74: Mixed developed and characterized by Pingarrón in 2006. Source: Pingarrón Alvarez, Victoria I. Performance Analysis of Hydraulic Lime Grouts for Masonry Repair. Masters Theses (Historic Preservation), University of Pennsylvania, 2006: 26.

[77] Silva et al. abstained from characterizing the drying shrinkage in their mud grouts due the complexity of its causes, such as external factors that are hard to simulate to obtain reliable results (Silva et al. 2012, 6). Lourenco and the team. Silva, Oliveira, Lourenco, Schueremans, and Miranda did not publish drying shrinkage results for their 2013 research.

[78] Pingarrón used glazed saucers to test the drying shrinkage, not the prisms.

### 6.4 Expansion & Bleeding

**Observations:** The graduated cylinder remained tightly sealed for 24 hours. During that time, absolutely no bleeding or expansion occurred. The weight of the graduated cylinder with the grout and parafilm seal was that of 1057.13 g. Once finished the weight was 1056.5 g, with only a slight weight change of 0.63 g.

### 6.5 Splitting Tensile Strength

**Results:** As previously mentioned, the tensile strength value obtained from this test is more likely to be higher than direct tensile strength measurements. The grout developed for Tumacácori averaged 0.50 $\mathrm{N/mm^2}$ (73.11 psi) in splitting tensile strength, and 0.26 $\mathrm{N/mm^2}$ (37.14 psi) in compressive strength.

| Mean of Maximum Load (lbf) | Mean of Splitting Tensile Strength (psi) | Standard deviation of Splitting Tensile Strength (psi) | Mean of Compressive Strength (psi) | Standard deviation of Compressive Strength (psi) |
|---|---|---|---|---|
| 943.10 | 75.86 | 11.32 | 36.26 | 4.49 |

Table 22: Splitting Tesnsile Strength results for grout. Source: Declet 2017.

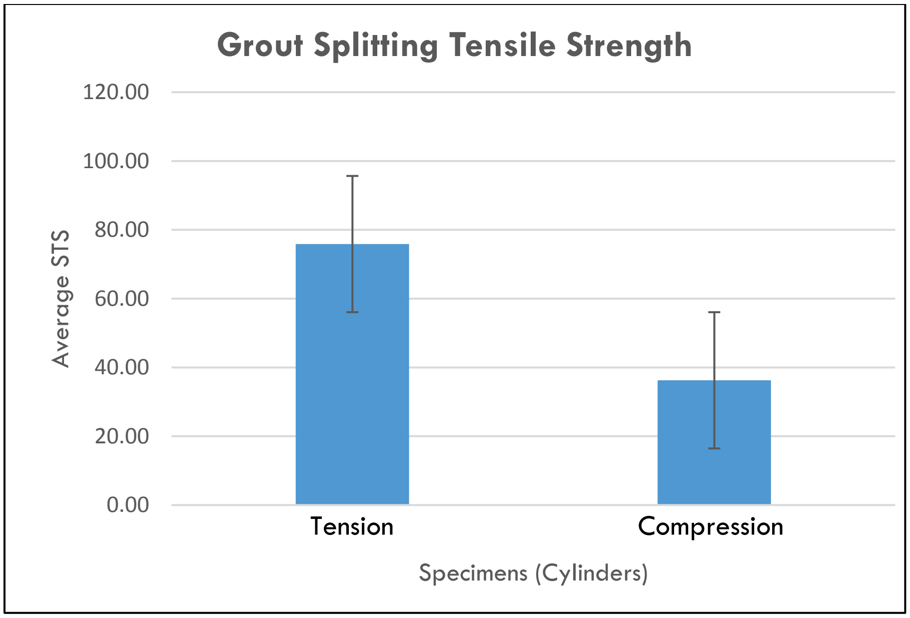



Table 23: Splitting Tensile Strength results graph. Source: Declet 2017.

Silva's rammed earth cylindrical specimens tested under compression resulted in an average of 1.26 $N/mm^2$, 20% more than the grout designed for Tumacácori.[79] However, the rammed earth was not designed to be a grout.

In comparison with Pingarrón's NHL and acrylic grouts (Range= 12.58-24.85 psi), the splitting tensile strength of the grout designed for Tumacácori was considerably stronger. However, the grout had a significantly lower compressive strength than Pingarrón's grouts. Similarly, the compressive strength of St.Astier's 1:2.5 NHL 3.5 grout is stronger in compression, 290 psi after 28 days, than the grout tested in this paper.

Nevertheless, the grout's strength should not exceed that of the original adherents: the adobe substrate and the lime plaster. The untreated soil's compressive

[79] The cylindrical specimens used by Silva's team measured 7.87" in height, and 3.93" in diameter. The rammed earth specimens were manufactured with soil from Odemira, Alentejo, and due to its high clay content, the soil was corrected by adding river sand and gravel obtained from crushed granite.

strength used for the Tumacácori adobe was tested in 1978 by Charles OBannon (OBannon 1978, 30). The compressive strength was around 3000 psf (20.83 psi). However, these results are not entirely representative of the actual adobes.[80] The soil samples were treated with electro-osmotic treatment prior to the compressive strength tests.

Table 4

TUMACACORI COMPRESSIVE STRENGTH

TREATMENT: SILICA GEL AND SODIUM CHLORIDE

| Voltage Gradient v/cm | Tube End | Time of Treatment | Compressive Strength PSF Treated | Compressive Strength PSF Untreated | Compressive Strength % Increase | Compressive Strength % Decrease |
|---|---|---|---|---|---|---|
| 1/4 | anode | 1 Day | 1917 | 3100 | --- | 38 |
| | cathode | | 2451 | 2800 | --- | 12 |
| 1/2 | anode | | 1055 | 2850 | --- | 63 |
| | cathode | | 1748 | 2800 | --- | 38 |
| 1 | anode | | 2961 | 2800 | 6 | --- |
| | cathode | | 2112 | 2900 | --- | 27 |
| 1/4 | anode | 2 Day | 2136 | 2900 | --- | 26 |
| | cathode | | 1408 | 2900 | --- | 51 |
| 1/2 | anode | | 3956 | 3000 | 32 | --- |
| | cathode | | 4029 | 2900 | 39 | --- |
| 1 | anode | | 1990 | 2900 | --- | 31 |
| | cathode | | * | * | * | * |
| 1/4 | anode | 4 Day | 2476 | 3000 | --- | 17 |
| | cathode | | 1262 | 3000 | --- | 58 |
| 1/2 | anode | | 2184 | 3000 | --- | 27 |
| | cathode | | 2015 | 3000 | --- | 33 |
| 1 | anode | | 2573 | 3000 | --- | 14 |
| | cathode | | 2016 | 3000 | --- | 33 |
| 0 | | | 2743 | 2900 | --- | 5 |

* Data unobtainable

Figure 75: O'Bannon compressive strength results for Tumacácori adobe soil. Source: O'Bannon, Charles E. Stabilization of Prehistoric Adobe Architecture by Electro-osmosis and Base Exchange of Ions (Phase II). Arizona: Arizona State University, 1978: 36.

On the other hand, plaster facsimiles resembling the mission's friable plaster were tested for splitting tensile strength in 2016 by Jang. Jang found that the average splitting tensile value of the untreated plaster was that of 451.27 psi, surpassing that of the tested

80 Soil cylinders were trimmed to a height twice the size of the diameter. These were later capped with Cylcap, a sulfur compound.

grout (Jang 2016, 77).[81] A summary below of the untreated and nanolime treated plaster samples tested by Jang:[82]

| | Control (A) | Consolidated (B) | Consolidated (C) |
|---|---|---|---|
| **Sample description** | Unconsolidated | 28 days curing | 1 year curing |
| **Maximum force (lbf)** | 113.7 | 148.7 | 242.4 |
| **Mean STS(psi)** | 451.2 | 654.7 | 1143.1 |
| **Stand. Dev. STS(psi)** | 90.4 | 99.7 | 80.8 |

Table 24: Splitting Tensile Strength results for consolidated plaster obtained by Jean Jang (unpublished).

### 6.6 Capillary Water Absorption

**Observations:** The test was performed twice with two separate sets of samples. The first used three grout columns 5 ¼' tall, and 1" diameter, while the second set measured 4 ¼" in height, and 1 ½" in diameter. As soon as the columns were placed in the perforated metal plate inside the water filled container, they began disintegrating. During both sets, rubber stoppers were placed next to the column for support, otherwise these would fall to their sides and break, or disintegrate unevenly. The first three samples all eventually fell. Sample 3 disintegrated completely in less than 2 hours.

Anticipating similar results, for the second set, the container, metal mesh, stoppers and water were weighed before and after placing the grout column. The columns had a larger surface area than the first set, so these took longer to disintegrate and loose balance. Results were still recorded for the second set.

[81] Jean Jang, ACL research associate and a recent program graduate, compared samples treated with nanolime consolidant to untreated samples and determined there was a 45% increase in splitting tensile strength. After a year of curing, Jean recently tested other consolidated samples and these saw a 153% increase in splitting tensile strength.
[82] The results for consolidated plaster after a year have not been published yet.

**Results:** The weight loss was probably due to dissociation of the clays in the soil grout.

### 6.7 Water retention

**Observations:** After several tries, leaving the vacuum cap unscrewed while the vacuum was on worked the best. The valve was opened at an angle of 25° to maintain the vacuum under 100 kPa. When the vacuum tube cap was kept sealed, pressure went as high as 96 kPa.

**Results:** The test was performed on three different materials to perfect the assembly and to make sure the test was running consistently. A summary of the tests below:

| Ingredients | Solid to Liquid ratio | Water content of the grout before suction | Weight of water extracted by suction | WRV % Water Retention Value |
|---|---|---|---|---|
| **NHL 3.5: Yellow Sand: Water** | 3.2: 1 | 90.98 g | -39.9 g | 143.86 |
| Notes: This mix is representative of hydraulic lime grouts. With the stopcock closed to the funnel (flask to atmospheric pressure) the pressure would not surpass 3.7 kPa. With the stopcock open, the pressure went as high as 83.7 kPa, and water poured heavily down the tube. Once the stopcock connected the funnel to the atmospheric pressure, the pressure went up to 96 kPa. | | | | |
| **Soil B (ASTM #8 sieve): Water** | 2.5: 1 | 61.25 | -17.39 | 128.39 |
| Notes: The tube was left unplugged, and while the stopcock was closed, the pressure remained at 0.3 kPa. The valve was fully opened. Soil B was assessed on Phase 1, but was not selected. It is however similar to Soil E, but water was added instead of HMP. It released less water than the NHL. | | | | |
| **Soil B (ASTM #8 sieve): HMP** | 2.5: 1 | 109.02 | -5.12 | 104.70 |
| Notes: Water was substituted for HMP to compare retention capability. The valve was not fully open, It was slightly rotated from 0° to 25°. The vacuum was regulated to 2.4 kPa prior to opening the stopcock. Once open, a balanced was reached after 40 seconds (78.6 kPa). It was left for an additional minute under a constant suction rate. The grout retained more water than the previous mixes. | | | | |

Table 25: Water retention and release comparison results. Source: Declet 2017.

A summary of the two batches of 2.5 Soil E: 1 HMP:

| WATER RETENTION AND RELEASE | | | | |
|---|---|---|---|---|
| Ingredients | Solid to Liquid ratio | Water content of the grout before suction | Weight of water extracted by suction | WRV % Water Retention Value |
| **2.5 Soil "E": 1 HMP (Batch 1)** | 2.5: 1 | 92.48 | **-4.4** | 104.76 |
| **2.5 Soil "E": 1 HMP (Batch 2)** | 2.5: 1 | 89.58 | **-4.4** | 104.91 |
| Notes: The valve was not fully open, It was slightly rotated from 0° to 25°. The vacuum was regulated to 2.4 kPa prior to opening the stopcock. Once open, a balance was reached after 1 minute (62.4 kPa). It remained for an additional minute under a constant suction rate. The grout retained a considerable amount of water in comparison to the other grouts tested. | | | | |

Table 26: Grout water retension and release results. Source: Declet 2017.

### 6.8 Permeability (WPT)

Water vapor transmission is indicated by the slope of the curve is determined by weight loss of the total assembly over time. A strong linear relationship, known as a high correlation, is reflected by a straight line. Materials with low permeance are not expected to result in high correlation. Thicker material and moisture retaining materials take a longer amount of time to reach a steady state. On the contrary, thin materials of low permeance do not need a long test duration to reach a steady state. For instance, a low permeance coating will reduce the water vapor transmission rate and increase the time necessary for the saturated material to dry.

**Observations:** The disks shrunk an average of 0.10in in diameter after a few days of curing. The temperature and RH were monitored, and kept at an average of 21.44°C and 49.86 RH%. After three weeks of curing, the samples were measured before and after placing in the oven. The specimens lost an average of 1.17% after being placed in the oven, and there was virtually no change in diameter and height of the disks during this process. The results of the WPT test were converted to g/h$\times \mathrm{m}^2$ in order to compare with outside data.

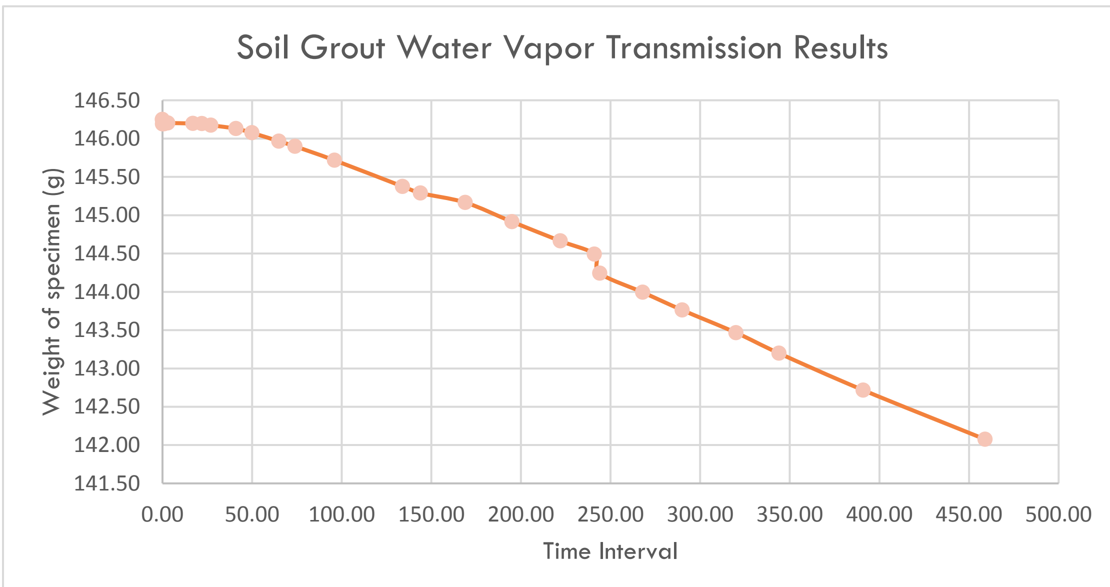



Table 27: Average wpt rates for 6 grout specimens.

**Results:** The greater the weight loss, the greater the sample's permeability. The average for the six specimens tested was 5.58 g/h$\times \mathrm{m}^2$, or 2.57 E-04 g/h$\times \mathrm{cm}^2$. In Bass's 1998 investigation, Fort Union adobe WPT reading was 6.10 g/h$\times \mathrm{m}^2$, which was lower than the grout cohorts Bass tested (Bass 1998, 74). These results could be compared to those obtained from the soil grout and they are quite similar, suggesting that the grout is compatible with adobe. However, WPT results for Tumacácori adobe would be needed to confirm this.[83] In comparison to the untreated plaster tested by Jang, the plaster was far less permeable than the grout, with an average of 1.62 E-05 g/h$\times$ $\mathrm{m}^2$.

**Water vapor transmission test results - Data**

| Grout Formula # | Grout Formula Ratio (weight) | Water Vapor Transmission Rate ($g/h \cdot m^2$) |
|---|---|---|
| 01 | 1MS : 1HL | 8.31 ±0.03 |
| 03 | 1MS : 1S : 2HL | 9.43 ±0.02 |
| 04 | 1MS : 1S : 4HL | 8.52 ±0.74 |
| 07 | 1MS:2.7S:2.5HL w/20% Rhoplex E-330 in $H_2O$ | 13.69 ±0.02 |
| 19 | MS : 1S : 2HL w/ 10% EL REY in $H_2O$ | 7.00 ±0.01 |
| 20 | 1MS : 1HL w/ 10% EL REY in $H_2O$ | 6.21 ±0.02 |
| NA | Fort Union Adobe (Boneyard) | 6.10 ±0.02 |

MS- Ceramic Microspheres HL- Hydrated Hydraulic Lime S- Quartz Sand
Rhoplex and El Rey- acrylic emulsion

**Table 17. Water vapor transmission rate test results - Phase II**

Figure 76 Angelyn Bass's tested grout formulations (1998). Source: Bass, Angelyn. Design and Evaluation of Hydraulic Lime Grouts for In Situ Reattachment of Lime Plaster to Earthen Walls. Masters Thesis, University of Pennsylvania, 1998: 73.

In comparison to other hydraulic lime grouts tested by Bass, all formulations tested were far more permeable than the 2.5 Soil: 1 HMP grout. The specimens employed were slightly larger in diameter than the ones tested here (2.75in diameter and 0.75in diameter). Those assemblies reached equilibrium in 10 days.[84] Pingarrón's testing of grouts coated with acrylic emulsion had significantly lower rates, 1.11-1.26 g/h$\times$ $\mathrm{m}^2$ due to the coating (Pingarrón 2006, 52).

83 WPT testing of the TUMA adobe was not performed due to limited availability of material.
84 Bass's tested specimens were coated with an acrylic emulsion which in some instances decreased their wpt rates, while in another increased it (Bass 1998, 74).

### 6.9 Shear Bond Strength (mock-up)

**Observations:** Shrinkage cracks were observed in the grout layer after uncovering the assemblies. The samples were allowed to dry for three weeks before performing mechanical testing. A metal grill was placed under the assemblies for the last week of curing to assure these dried evenly. The 19 assemblies were transported on a covered cart from the laboratory to the LRSM mechanical testing room.[85] Transportation of the assemblies was somewhat problematic as the pavement is very uneven.

The operator, Dr. Alex Radin, placed a clamp on the adobe blocks in order to keep them fixed and to insure an even surface contact with the platen.[86] After testing, the samples were transported back to the ACL laboratory, where the width and length of the grouted area was recorded after breaking was measured. Photographs of each assembly were also taken to describe failure behavior. The breaking surface of each specimen was annotated as to where the break occurred (at the adobe or plaster interface or in the grout, and the fracture appearance: either conchoidal (shell-like fractures) or planar (even).

100% contact of the grout with the adhered surfaces was observed no matter how the assembly broke which indicated good injectability. In most instances the grout either broke at the interface with the adobe or in the adobe, never at the plaster interface. This reveals the grout adhered extremely well to the friable plaster. The surface shrinkage

---

85 The Laboratory for Research on the Structure of Matter is located two blocks away from the School of Design.

86 The Instron Electromechanical Testing Machine, Model 4206, was used for this test.

cracks initially observed during the drying period, were also present within the grout, yet the grout remain well bonded to the adobe adherend even after testing

| Image | Unconsolidated | Gap width | Observations |
|---|---|---|---|
|  | (-) B1 | 1/2" | Shrinkage cracks were less apparent. 100% contact area. Extremely well adhered to the plaster.<br>The grout was stronger than the adobe in some areas.<br>The surface mostly remained flat, meaning it broke at the interface. |
|  | (-) B2 | 1/2" | Shrinkage cracks visible. 100% contact area. Extremely well adhered to the plaster.<br>Adobe retained some of the grout.<br>Grout is less than 0.6925" thick.<br>The surface is more conchoidal than flat. |
|  | (-) B3 | 1/4" | Shrinkage cracks visible. 100% contact area. Extremely well adhered to the plaster.<br>The top edge is conchoidal, while the rest most likely broke at the interface. Grout thickness on the side is less than 0.6020". |
|  | (-) B4 | 1/4" | Shrinkage cracks visible. 100% contact area. Extremely well adhered to the plaster.<br>The grout pulled some of the adobe on the left edge.<br>Some of the adobe took straw and pebbles with it.<br>The grout edges is less than 0.4270".<br>Some conchoidal orifices, but it mostly broke at the interface. |
|  | (-) B5 | 1/4" | Shrinkage cracks visible. 100% contact area. Grout extremely well adhered to the plaster.<br>Break predominately at the interface, but the top displays conchoidal fracture within the adobe. |

| | | | |
|---|---|---|---|
|  | (-) B6 | 1/4" | Shrinkage cracks visible. 100% contact area. Grout well adhered to the plaster and adobe with around 40% of the grout adhering to the adobe<br>The surface is somewhat conchoidal. |
|  | (-) B8 | 1/2" | Shrinkage cracks were less apparent. 100% contact area.  Grout extremely well adhered to the plaster.<br>to the adobe on the right side.<br>The fractureis mostly conchoidal. |
|  | (-) B9 | 1/4" | Shrinkage cracks were less apparent. 100% contact area.  Grout extremely well adhered to the plaster.<br>A large area of the adobe was adhered to the grout on the upper right corner. |
|  | (-) B10 | 1/2" | Shrinkage cracks were less apparent. 100% contact area.  Grout extremely well adhered to the plaster.<br>Adobe substrate well bonded to the grout, indicating it was stronger than the grout. Less than 0.6” of grout remained attached to the adobe. There were some concoidal fracture but the fracture surface was mostly flat. |
| **Image** | Consolidated | Gap width | Observations |
|  | A1 | 1/4" | Shrinkage cracks are visible. 100% contact area.  Grout extremely well adhered to the plaster.<br>Some of the grout remained attached to the adobe but broke mostly at the interface, evidenced by flat surface. However, there are some conchoidal fractures in the adobe surface. Some of the straw from the adobe was pulled unto the grout layer. |

| | | | |
|---|---|---|---|
|  | A4 | 1/4" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>A small section of the adobe substrate bonded to the grout layer.<br>The surface fracture is conchoidal at the far left side of the assembly. The remaining surface is a combination. |
|  | A6 | 1/4" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster and broke at the interface (mostly flat surface). |
|  | A7 | 1/4" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>Grout layer is less than 0.4”. Mostly broke at the interface with the adobe. |
|  | A8 | 1/2" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>Grout bonded to the adobe on the corner upper middle section. |
|  | A9 | 1/4" | No shrinkage cracks. 100% contact area. Grout extremely well adhered to the plaster.<br>The grout was stronger than the adobe causing a conchoidal pull out of around 0.8” of the adobe substrate. |
|  | A10 | 1/4" | Less shrinkage cracks than other assemblies. 100% contact area. Grout extremely well adhered to the plaster.<br>Grout was weaker than the adobe, breaking at the top edge with a conchoidal surface, while the rest broke at the interface. |

| | | | |
|---|---|---|---|
|  | A11 | 1/2" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>Some of the grout remained attached to the adobe.<br>Some conchoidal fracture. |
|  | B11 | 1/2" | *First one to be tested.<br>Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>Fracture at the grout-adobe interface. |
|  | B14 | 1/2" | Shrinkage cracks are visible. 100% contact area. Grout extremely well adhered to the plaster.<br>The grout pulled 0.2" from the adobe, but fracture mostly at the interface. |

Table 28: Observations for all assemblies tested for shear bond strength. Source: Declet 2017.

**Results:** The average shear bond strength for assemblies with unconsolidated plaster was 4.21 lb $\times\ \mathrm{in}^{-2}$, and 4.98 lb $\times\ \mathrm{in}^{-2}$ for assemblies with nanolime consolidated plaster. The bond strength of the grout to the consolidated plaster was slightly higher than to the unconsolidated plaster. The average breaking strength for consolidated plaster was higher as well.

| | Width of grout area **w (in)** | Length of grout area **l (in)** | Breaking load **F (lb)** | Shear Bond Strength **(lb*in–2)** |
|---|---|---|---|---|
| Unconsolidated | 2.78 | 3.69 | 43.23 | 4.21 |
| Consolidated | 2.81 | 3.67 | 51.30 | 4.98 |

Table 29: Shear Bond Strength results for assemblies. Source: Declet 2017.

| | Mean of Maximum Load **(lbf)** | Mean of Shear Bond Strength **(psi)** | Standard deviation of SBS **(psi)** | T-Test P Value | T-Test 2-Tail P |
|---|---|---|---|---|---|
| Unconsolidated | 43.22666667 | 4.21 | 1.7 | 0.015 | 0.68 |
| Consolidated | 51.295 | 4.98 | 3.85 | | |

Table 30: Analysis of shear bond strength results for assemblies. Source: Declet 2017.

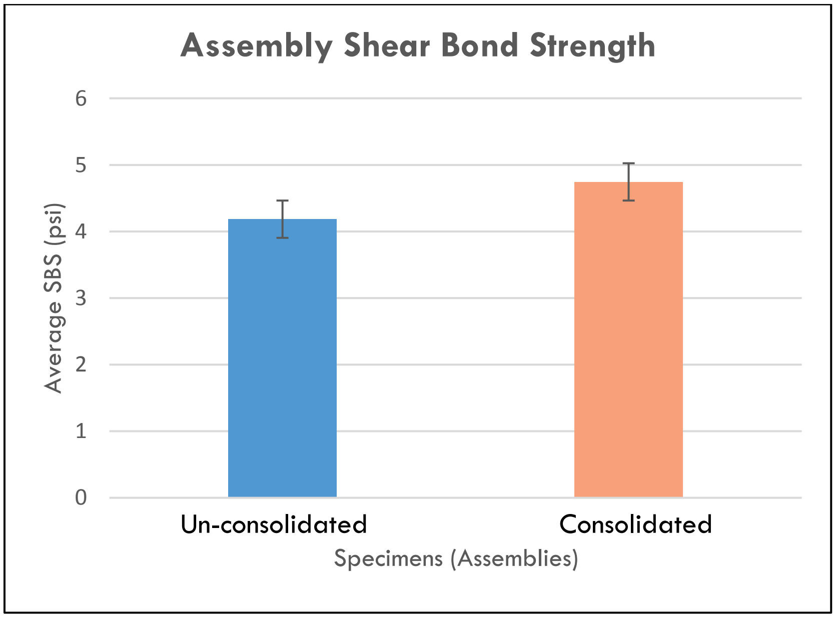



Table 31: Graph comparing shear bond strength results of un-consolidated and consolidated assemblies. Source: Declet 2017.

## Chapter 7: Conclusions and Recommendations

The selected grout should be physically and chemically compatible with the original substrate and coatings, have sufficient flow without clumping, and its volume shrinkage once hardened should be minimal (low water content). In terms of mechanical strength, the injection grout should not create excessive stresses on the original plaster. The grout should also be lightweight, allow passage of water vapor and provide a sufficient bond strength at the interfaces. Any change or degradation over time should not introduce harmful substances or deleterious effects.

### 7.1 Testing Conclusion

| | Sample Schedule | | |
|---|---|---|---|
| | Test | Desired Grout Properties | Results for TUMA Grout |
| Wet Grout Testing | **Flow/ Viscosity** | Low viscosity/ good fluidity | Both batches flowed easily, and absolutely no settling of course fraction occurred. |
| Wet Grout Testing | **Wet Density** | Low density | The grout's wet density was an average of 1.87 g/cc. In terms of compatibility, the grout has a smaller density than that of Tumacácori. |
| Wet Grout Testing | **Drying Shrinkage Test** (qualitative-saucers and prisms) | Minimal shrinkage | The grout placed in the terra cotta saucers performed well. The grout did not crack, but it did shrink. The average percent shrinkage for the six prisms was 29.41%, and the standard deviation is 9.56. |
| Wet Grout Testing | **Expansion & Bleeding** | No bleeding | The graduated cylinder remained tightly sealed for 24 hours. During that time, absolutely no bleeding or expansion occurred. |
| Dry Grout Testing | **Water retention** | Reasonable water retention | The TUMA grout showed a strong resistance to having its water absorbed. |
| Dry Grout Testing | **Permeability** (water vapor transmission) | Good water vapor permeability | Low-Average permeability. Similar permeability to Fort Union adobe. |
| Dry Grout Testing | **Splitting Tensile Strength** | Tensile strength similar or less than historic materials. | The average splitting tensile value was lower than the splitting tensile value of the untreated plaster. |
| Mock-up | **Shear Bond Strength** (adhesion) | Adhesion strength similar or less than historic materials. | Shear bond strength was lower than plaster and adobe. |

Table 32: Overall results for grout testing. Source: Declet 2017.

Given the results, the grout appears to have performed successfully for wet and hardened properties. The desired viscosity for a grout should be low. The grout tested has a moderate viscosity, flowed easily, and due to the use of the defflocculant there was no settling of coarse fraction. The grout's wet density was also very low, and given the plaster of the mission is quite friable, any significant added weight could result in further detachment from the surface. Another desirable property of the grout is its ability to retain a significant amount of water. Once inserted in the assembly, porous materials such as the grout and plaster will try to absorb the water in the grout. By introducing a grout that is able to retain the liquid portion, the amount absorbed by the adjacent original materials is limited. In the case of soil grouts, this will allow the grout to dry slowly avoiding excessive shrinkage. The grout also did not bleed or expand during testing.

Regarding the percent shrinkage, the prism shrinkage was moderate. The grout was also vapor permeable displaying a similar reading to Fort Union adobe. However, if sufficient original Tumacacori adobe is available, permeability tests should be performed.

The grout also performed well for both tensile strength and shear bond strength. The tensile strength value of the grout was less than that of the friable plaster, both consolidated and unconsolidated. When injected and tested for shear bond strength, the grout also adhered successfully to the lime plaster and the adobe squares, possibly due to the similarity between the grout and the original materials. Overall, the successful results for the grout tested reiterate the use of compatible materials to achieve a successful grout formulation.

### 7.2 Future Testing and Recommendation

**X-Ray Diffraction**: An initial concern was the introduction of salts by using sodium hexametaphosphate. Additional testing should be performed to analyze the salts present in the mix. Many other researchers that have used HMP in their soil grouts, such as Silva, Schueremans, Oliveira, Gyssels, Iyer, and Lourenco, have not encountered efflorescence as a result of the grout (Iyer 2014; Silva and Oliveira 2009; Silva et al. 2012; Lourenco et al. 2013). However, it is mentioned that a soil grout must present chemical stability over time, and its salt content has to be limited in order to prevent efflorescence (Silva et al. 2010, 4).

**Three Point Bending Flexural Test:** The New Mexico adobe used for the mockups should be tested for three point bending, to further characterize and compare its breaking load with that acquired by the grout and plaster.

**In situ Preparation:** The following steps to develop the grout formulation include formulating a series of in situ tests and trials. Prior to application as part of pretreatment assessment, the areas of plaster separation to be grouted should be indicated on the existing rectified images. Also, the condition of the plaster, extent of the plaster separation and gap for each plaster should be recorded. The entry points for the catheters should be determined as well. Once in situ tests are installed, the grouted area should be checked daily and monitored, including ambient temperature and relative humidity and any changes should be measured. If possible nondestructive methods of void detection and reattachment/void filling should be pursued before and after treatment to determine overall efficacy of the grouting method.

## Bibliography

Air Force Combat Climatology Center (AFCCC). "Tucson, Arizona." Engineering Weather Data Handbook. Raw Data. https://www1.ncdc.noaa.gov/pub/data/EngineeringWeatherData_CDROM/engwx/tucson_az.pdf.

Albert, Lewis S. Memorandum for the Superintendent of Tumacacori and Chiricahua, San Francisco, CA, November 2, 1988.

Arendt, Nicole M. Report on the April 2010 Repair to the Plaster and Adobe Failure on the Upper WEST Exterior Wall of the Sanctuary of San Jose de. 2010.

Arendt, Nicole M. Report on the Effects of the January 2010 Rains on the Sacristy at Tumacacori National Historic Park. 2010.

Ashurst, John. *Mortars, Plasters and Renders in Conservation*. London: Ecclesiastical Architects' and Surveyors' Association, 1983.

Attwell, Walter G. and Gene H. Gordon. *Report on Proposed Stabilization Mission San Jose de Tumacacori.* San Francisco, CA: United States Department of the Interior National Park Service, 1935.

Bass, Angelyn. *Design and Evaluation of Hydraulic Lime Grouts for In Situ Reattachment of Lime Plaster to Earthen Walls*. Masters Thesis, University of Pennsylvania, 1998.

Bass, Angelyn and Douglas Porter. Assessment, Emergency Stabilization and Treatment of Painted Plasters in the Mission Church at Tumacacori National Historic Park, School of Architecture and Planning, 2012.

Bicer-Simisr, Beril and Leslie Rainer. *Evaluation of Lime-Based Hydraulic Injection Grouts for the Conservation of Architectural Surfaces: A Manual of Laboratory and Field Test Methods.* (2011), Los Angeles: Getty Conservation Institute.

Brown, Paul Wencil, Carl R. Robbins, and James R. Clifton. "Adobe. II: Factors Affecting the Durability of Adobe Structures." *Studies in Conservation* 24, no. 1 (1979): 23-39. doi:10.2307/1505920.

Caywood, Louis R. The Tumacacori Interpretive Program. United States Department of the Interior, National Park Service, 1944.

Caywood, Louis R. Memorandum for the Superintendent of Southwestern National Monuments, Nogales, AZ, July 11, 1941.

Chambers, George J. Tumacacori Preservation Project: Field Activities 1977, 1978, and 1979. Western Archeological Center, 1981.

Chambers, George J. Memorandum for the Chief of Division of Archaeology, Tumacácori, AZ, March 12, 1986.

Chan, Jocelyn. *An Investigation of the Painted Finishes of Mission San José de Tumacácori's Façade: At the Interface of Materials Analysis, Conservation, and Cultural Confluence*. Masters Thesis. University of Pennsylvania, 2016.

Clemensen, Berle A. Historic Structure Report: A History of the Anglo Period Tumacacori National Monument Arizona. Denver Service Center, Historic Preservation Division. National Park Service. United States Department of the Interior, 1977.

Clifton, James R. Preservation to George Cattanach of Western Archeological Center, Tucson, AZ, December 3, 1976.

Crosby, Anthony. Historic Structure Report: Tumacacori National Monument Arizona. United States Department of the Interior, 1985.

Crosby, Anthony. "A Preservation Monitoring System at Tumacacori National Monument." *APT Bulletin of the Association for Preservation Technology* 10, no. 2, Association for Preservation Technology International (APT), 1978: 47-76. http://www.jstor.org/stable/1493612.

Crosby, Anthony. "Monitoring Moisture at Tumacacori." *APT Bulletin of the Association for Preservation Technology* 19, no. 4, Association for Preservation Technology International (APT), 1987: 32-44. http://www.jstor.org/stable/1494147.

Davis, John M. Davis John to Earl Jackson, Tumacácori, AZ, February 12, 1948.

Davis, John H. John Davis to Dorothy Hall, San Francisco, CA, March 25, 1977.

Drachman Institute Heritage Conservation. Interior Condition Assessment Report. Tumacácori National Historic Park. College of Architecture, Planning, and Landscape Architecture. The University of Arizona. In conjunction withL Desert Southwest Coopertive Ecosystem Studies Unit. July 2006.

Ferron, Amila. *The Consolidation of Earthen Surface Finishes: A Study of Disaggregating Plasters at Mesa Verde National Park.* Masters Thesis. University of Pennsylvania, 2007.

Getty Conservation Institute. *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation,* edited by Erica Avrami, Hubert Guillaud, and Mary Hardy (2008), Los Angeles: Getty Conservation Institute.

Getty Conservation Institute. *The Conservation of Decorated Surfaces on Earthen Architecture: Proceedings of an International Symposium Organized by the Getty Conservation Institute and the National Park Service, Mesa Verde National Park, Colorado, USA, September 2225, 2004*, edited by Leslie Rainer and Angelyn Bass Rivera (2006), Los Angeles: Getty Conservation Institute.

Giffords, Gloria Fraser. *Sanctuaries of Earth, Stone, and Light: The Churches of Northern New Spain, 1530-1821*. Tucson: U of Arizona, 2007.

Graham, John. *Tumacácori National Historical Park: Geologic Resources Inventory Report.* Report no. NPS/NRSS/GRD/NRR-2011/439. U.S. Department of the Interior, Natural Resource Stewardship and Science, National Park Service. Fort Collins, CO: August 2011. https://www.nature.nps.gov/geology/inventory/publications/reports/tuma_gri_rpt_body_print.pdf.

Grimmer, Anne. *Preservation Briefs 22: The Preservation and Repair of Historic Stucco*. Washington: U.S. Dept. of the Interior, National Park Service, Preservation Assistance Division, 1990.

Hamard, Erwan, Jean C. Morel, Fernanda Salgado, Alain Marcom, and Nicolas Meunier. "A Procedure to Assess Suitability of Plaster to Protect Vernacular Earthen Architecture." *Journal of Cultural Heritage* 14 (April 5, 2012): 109-15. http://dx.doi.org/10.1016/j.culher.2012.04.005.

Henderson, Sam R. Stabilization Report: Tumacacori National Monument 1972. Arizona Archaeological Center, Ruins Stabilization Unit: Tucson, AZ, 1972.

Henry, Alison, and John D. Stewart. *Practical Building Conservation. Mortars, Renders & Plasters*. Farnham: Ashgate, 2012.

Herreras, Eleazar D, James D. Kriegh, and Hassan A. Sultan. Investigation and Inspection of Historic Structures. The Complex at Tumacacori National Monument. Second

Phase Consulting Report. United States Department of the Interior, National Park Service, 1974.

Iyer, Nityaa Lakshmi, *Performance Evaluation of Clay Grout Formulations for Structural Cracking in Historic Earthen (Mud Brick) Buildings.* Masters Theses (Historic Preservation), University of Pennsylvania, 2014.

Jackson, Earl. Memorandum for the Regional Director Region Three, Nogales, AZ, May 25, 1946.

Jackson, Earl. Memorandum for the Regional Director Region Three, Tumacácori, AZ, September 26, 1947.

Jackson, Earl. Memorandum for the General Superintendent of Southwestern National Monuments, Tumacácori, AZ, July 31, 1951.

Jackson, Earl. Earl Jackson to Regional Director Region Three, Tumacácori, AZ, February 5, 1948.

Jackson, Earl. Earl Jackson to Raymond E. Davis and Division of Civil Engineers at University of California, Tumacácori, AZ, April 13, 1948.

Jackson, Earl. Earl Jackson to Rutherford J. Gettens, Tumacácori, AZ, February 27, 1949.

Jang, Jean. *Performance Evaluation of Commercial Nanolime as a Consolidant for Friable Lime Based Plaster*. Masters Thesis. University of Pennsylvania, 2016.

McHenry, Paul Graham. *Adobe and Rammed Earth Buildings: Design and Construction*. University of Arizona Press, 1989.

McHenry, Paul Graham. Report on Research, Investigations, Conclusions and Recommendations for Moisture Control and Plastering at Tumacacori National Monument, AZ. Corrales, NM, 1978.

Michoiová Dagmar and Palva Rovaníková. "High-Calcium Lime Mortar: The Effects of Traditional Preparation and Curing" *APT Bulletin,* Vol. 39, No. 4, Association for Preservation Technology International (APT), 2008.

Miller, Hugh. "Unusual Weather Takes Toll on Mission Church." News Article. *U.S. Department of the Interior. National Park Service.* February 6, 1985.

Moss, Jeremy. "Of Adobe, Lime, and Cement: The Preservation History of the San José De Tumacácori Mission Church." *NPS Archeology Program: Research in the Parks*, National Parks Service: U.S. Department of the Interior, 2008.

Moss, Jeremy. "Missions of Tumacácori National Historic Park Overview Draft", South West Learning, National Parks Service.

Mulhern, Tom. Memorandum, Tumacácori, AZ, May 31, 1985.

O'Bannon, Charles E. Stabilization of Prehistoric Adobe Architecture by Electro-osmosis and Base Exchange of Ions (Phase II). Arizona: Arizona State University, 1978.

Padovnik, Andreja and Francesca Piqué, Albert Jornet & Violeta Bokan-Bosiljkov. *Injection Grouts for the Re-Attachment of Architectural Surfaces with Historic Value—Measures to Improve the Properties of Hydrated Lime Grouts in Slovenia.* International Journal of Architectural Heritage, Vol.10, No.8, 2016: 993-1007.

Percious, D.J. and M. Norvelle. *Report on the Examination of Available Evidence on the Deterioration of the Walls of the Tumacacori Mission*. Laboratory of Native Development, Systems Analysis and Applied Technology. Office of Arid Lands Studies. Tucson, AZ: University of Arizona, 1978.

Phillips, Morgan W. "Adhesives for the Reattachment of Loose Plaster." *Bulletin of the Association for Preservation Technology* 12, no. 2 (1980): 37-63. http://www.jstor.org/stable/1493739.

Physical Science Technician. Physical Science Technician to Chief, Division of Cultural Properties Conservation, Tumacácori, AZ, July 24, 1978.

Pingarrón Alvarez, Victoria I. *Performance Analysis of Hydraulic Lime Grouts for Masonry Repair*. Masters Theses (Historic Preservation), University of Pennsylvania, 2006.

Raithel, Kenneth Jr. Memorandum for the Regional Director of the Western Regional Office, Tumacácori, AZ, December 6, 1982.

Richey, Charles A. Report of Inspection. United States Department of the Interior: National Park Service, Coolidge, AZ, 1941.

Rickerby, Stephen, Lisa Shekede, Fan Zaixuan, Tang Wei, Qiao Hai, Yang Jinjian, and Francesca Piqué. Development and Testing of the Grouting and Soluble-Salts Reduction Treatments of Cave 85 Wall Paintings. In *Conservation of Ancient Sites on the Silk Road, Second International Conference on the Conservation of Grotto*

*Sites, June 28-July 5, 2008,* Mogao Grottoes, Dunhuang, Gansu Province, The People's Republic of China. Los Angeles: J. Paul Getty Trust.

Ringenbach, Ray B. Ray B. Ringenbach (Superintendent) to Archaeologist in Charge of Ruins Stabilization, Tumacácori, AZ, September 11, 1955.

Rigenbach, Ray. Ray Rigenbach to Superintendent of Fort Union National Monument, April 1954.

Robbins, Carl. *Characterization of Adobe Specimens for Tumacacori National Monument, Arizona.* Quarterly Progress Report. Prepared for the U.S. National Park Service. 1976.

Sewell, Joseph L. Memorandum for Participating Offices: SOAR, WACC, DSC, Tumacácori, AZ, April 4, 1984.

Simon, Stefan and Daniel Geyer. *Comparative Testing of Earthen Grouts for the Conservation of Historic Earthen Architectural Surfaces*. Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage. The Getty Conservation Insititute and the Mali Ministry of Culture, 2008.

Silva, R.A. and L.Schueremans, D.V.Oliveira, K.Dekoning, and T.Gyssels. "On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion." ISISE, University of Minho, Portugal and Catholic University of Leuven, Belgium, 2012.

Silva, R.A. and D.V.Oliveira. "Strengthening of masonry and earthen structures by means of grouting- design of grouts." ISISE, University of Minho, Portugal and Catholic University of Leuven, Belgium, 2009.

Silva, R.A. and D.V.Oliveira, P.B. Lourenco, L.Schueremans and T.Miranda. Experimental investigation on the repair of rammed earth by means of injection of mud grouts." ISISE, University of Minho, Portugal and Catholic University of Leuven, Belgium, 2013.

Steen, Charlie, Rutherford J. Gettens and Jimmie Trujillo. "Tumacacori Interior Decorations." *Arizona Historical Society* 3, no.3 (Fall 1962): 7-33. http://www.jstor.org/stable/41700762.

Steen, Charlie R. Memorandum for the Associate Regional Director, Santa Fe, NM, March 5, 1946.

Sudderth, W.W. The Nave and Bell Tower Stabilization Report 1973. Tumacacori National Monument. Ruins Stabilization Unit. Arizona Archaeological Center. Tucson, Arizona, 1974.

Türköz, Murat and Hasan Tosun, *The use of methylene blue test for predicting swell parameters of natural clay soils.* Research Paper. Civil Engineering Department and Agricultural Faculty, Eskisehir Osmangazi University, 26480, Eskisehir, Turkey, 2010.

Unknown Author. Report on Current Conditions of Each Historical Structure at Tumacácori National Monument. Unknown Publisher. January 1, 1941.

Unknown Author. Report on Plaster Cracking and Leaks Associated with the West Sanctuary Window. Tumacácori National Historic Park. Unknown Publisher. July 6-8, 2009.

Unknown Author. Tumacacori Mission Dome Project Update History. Unknown Publisher. 1986.

Vargas, Julio and Bhawna Dandona, Marcial Blondet, Claudia Cancino, Carlos Iwaki, and Kathya Morales. *An Experimental Study of the Use of Soil-Based Grouts for the Repair of Historic Earthen Walls and a Case Study of an Early Period Buddhist Monastery*. Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage. The Getty Conservation Institute and the Mali Ministry of Culture, 2008.

Vargas J., Blondet M., Cancino C., Ginocchio F., Iwaki C. and Morales K. Experimental results on the use of mud-based grouts to repair seismic cracks on adobe walls. In: D'Ayala D. and Fodde E. (Eds.) Preserving Safety and Significance, Proceedings of the VI International Conference on Structural Analysis of Historic Constructions 2008, Bath, UK, 2008: 1095-1099.

Woodward, Arthur. Report of Investigation of Excavations at Tumacacori National Monument, March, 1935. Berkeley, CA, 1935.

Yancey, Charles. Charles Yancey to George S. Cattanach, Jr., Tucson, AZ, July 24, 1979.

## Appendix A: Plaster Petrographic Analysis

### Sampling and methodology

Sample S-13 (interior plaster) has an uncovered slip, was grinded in oil (water sensitive material) and was vacuum impregnated with an epoxy resin by consulting geologic laboratory National Petrographics Service, Inc. By mounting the section onto a slide, transmitted light is allowed to pass through.  The sample was sourced January 2017 by Frank G. Matero, and was trimmed in the ACL Laboratory to fit the dimensions of the thin section.

Sample 25 was grounded to 28-30 microns thick in oil and cover slipped. Like Sample S-13, the samples was impregnated with clear epoxy. The sample was sourced from fallen plaster fragments collected by Alex Lim. The sample was trimmed and prepared by National Petrographics Service, Inc.

Both samples were analyzed at the Penn Museum's Center for the Analysis of Archaeological Materials mostly using a research grade compound transmitted microscope, Zeiss AX10 microscope. Characterization of the samples was done by analyzing the soil micromorphology, such as groundmass, and identifying inclusions and rock fragments. Rock fragments and minerals were determined by observing their optical properties, such as relief, pleochroism, birefringence, and extinction, amongst others.

### Geological Context

The structure lies within the Basin and Range geological province and its located north of Nogales, Arizona. Surrounding the Tumacácori Mission Unit is the Santa Cruz River Valley of southern Arizona, which flows southward into Mexico past Sonora. The building also sits along a natural drainage system that travels from the Tumacácori Mountains to the Santa Cruz River (Moss 2008, 1). The Basin and Range province is said to have formed 15 million years ago, and the surrounding mountains were given its shape by volcanic rocks from eruptions occurring 23-27 million years ago (Graham 2012, 1). For this reason, pyroclastic materials formed from lava flow are found to be a few thousands meters thick (Graham 2012, 2).

Eroded sediment originating from the nearby mountains has covered the surface of the faults and adjacent basins. The oldest rocks in the region are granitic, igneous, intrusive rocks, which might date as far as 164 million years ago. These are classified as quartz monzonite and are characterized by 35% plagioclase, 36% potassium feldspar minerals and 20% quartz. The surface geology of the area is mainly composed of Holocene floodplain and river deposits that have eroded. The Santa Cruz River valley contains a considerable amount of alluvium, “which generally has a high permeability typical of sand and gravel deposits but which locally may be characterized by a predominance of fine sands and silts” (Percious 1978. p.3).

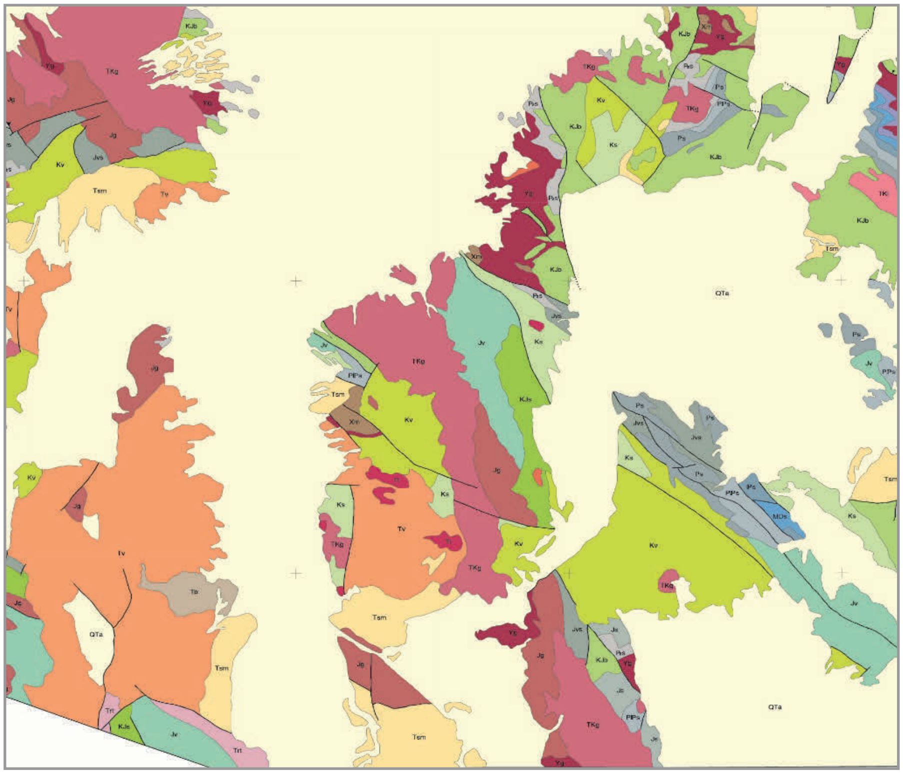


Figure 77: Close-up geological map location of Tumacácori. Source: Oland, G.P and D.M. Hirschberg, Digital Geologic Map of the Tucson and Nogales: A Digital Database for the 1990 Peterson and others' Map. USGS Department of the Interior U.S. Geological Survey, 2001. http://geopubs.wr.usgs.gov/open-file/of01-275

Quaternary deposits surround the location are identified by alluvium deposited from larger streams near the mountains. Qts, defined as a basin fill deposit, are composed of older eroded alluvial deposits as described above. Surfaces are commonly found as eroded ridges and deep valleys, with varying deposit thicknesses. Deposits are often sub angular to sub rounded boulders, cobbles, and gravels compressed with layers of sand, silt and clay. Alluvium and sedimentary rocks form QTa with varying degrees of consolidation. Caliche-cemented sand, silt, and gravel deposits of conglomerate, sandstone, and siltstone, as well as small amounts of lacustrine are found in this formation. Sedimentary rocks, such as conglomerate, sandstone, and finer grained rocks are also found in the Tsm (Miocene) and Ks (Cretaceous) groups.

As previously mentioned, volcanic rocks from lava flow are found in the area Tv, such as basalt, andesite, trachyandesite, flow breccia, rhyolitic, ltitic, dacitic, and potassium metasomatized volcanic rocks. A different group of minerals and rocks is found on the

TKg group from the Paleocene period. These are granitoid rocks, described as medium to fine grained biotite hornblende granodiorite, granite, diorite, and gabbro. More granitoid rocks are found in the Jg (Jurassic) group, containing (coarse to fine grained granite, granodiorite), quartz syenite, syenodiorite, (diorite, and rhyolite), rhyolite porphyry, and aplite intrusions. Similarly, Yg (Middle Proterozoic) groups also contain granite, as well as megacrysts of K-feldspar. Outcrops in this group are composed of pegmatite, alaskite, and aplite.

Finally, metamorphic rocks are found in the Xm (Early Proterozoic) group. These have green schist, amphibolite-facies, metahypabyssal, and metaplutonic rocks.

**Petrographic Results**

TUMA S-13 contains several air bubbles, and does not have a coverslip like TUMA 25. This contributes to TUMA S-13's grainy appearance and pronounced alteration.

Most of the mineral found in both the exterior and interior sample indicate these were locally sourced. The identification matches the local geology, mostly igneous, granitic rocks (Tv, TKg, Jvs, Jg, Yg). Far more felsic minerals than mafic minerals were found for both samples.

Rock fragments in both samples are mostly identified as trachyandesite and andesite. For TUMA S-13, these rock fragments are very weathered. Upon close inspection, some small minerals are observed (100x). Some of these igneous rock fragments appear to be grading into a different rock, perhaps a high clay rock. Some trachyandesite fragments on both samples contain large phenocrysts of a heavily weathered mafic mineral.

Some andesite fragments found in TUMA S-13 appear to be metamorphosing with some alteration. The presence of the epidote indicates that is metamorphosing. Some andesite rock fragments are more intrusive and contain interlocking minerals. Andesite rock fragments for TUMA 25 contain less phenocrysts than other rock fragments, while others have a large inclusions of opaque minerals. Granite rock fragments on both samples have an ultramafic composition. There are more quartz inclusions than the in the Granite Rock group found for TUMA S-13. Some rock fragments for both samples contains inclusions of an altered mafic mineral that is very yellow and orange in color in both PPL and XPL.

Amphibolite rock fragments are found in the exterior plaster sample (TUMA 25), but not in TUMA S-13. Also, a larger amount of quartz and calcite minerals is found in TUMA 25 than in TUMA S-13. Potassium feldspar is also common in TUMA 25.

For TUMA 25, coarse sand appears to have been used as a filler. It also contains more individual minerals, such as calcite, than rock fragments in comparison to TUMA S-13. This might suggest the preparation of the binder for the interior and exterior plaster was different. This suggests the plaster for both the interior and exterior was prepared at different times.

**Conclusion/ Discussion**

Most rock fragments are igneous rocks for both samples. Outcrops of metamorphic rock were far less abundant. Amphibolite rock fragments were also commonly found in TUMA 25. The rock fragments and minerals found in TUMA S-13 are slightly more weathered than those found in TUMA 25. However, this might be due the lack of coverslip on TUMA S-13. For TUMA S-13, the gypsum finish layer is very friable and there is a void underneath indicating it's detached. Conversely, the gypsum finish layer on the exterior plaster sample, TUMA 25, is attached to the rest of the layers.

**Petrographic description of the fabric groups**

**Microstructure**

TUMA S-13 (interior) is very porous and contains large voids. TUMA 25 (exterior) is porous, yet the voids are smaller in size and are evenly spaced amongst each other.

**Groundmass**

The matrix for both TUMA S-13 and TUMA 25 is a clay-silt matrix, mostly micrite clay. However, there is sparite silt as well with sand size crystals of calcite. It appears to be poorly consolidated. The color of the groundmass ranges from lighter browns to darker browns and to black in PPL. While in XPL, the groundmass is a darker brown. Overall, the samples have a lime binder.

**Inclusions** (c:f:v)

The inclusions in TUMA S-13 are very poorly sorted. The samples contains large fragments of rocks, as well as small particles. Inclusions in TUMA 25 are moderately sorted to poorly sorted. The amount of fines in TUMA 25 is larger than TUMA S-13

$c:f:v_{0.125mm}$= ca.45:35:20 (TUMA S-13)
$c:f:v_{0.125mm}$= ca.25:65:10 (TUMA 25)

**Group 1: TUMA S-13 (Interior Plaster Sample)**

*Fine Fraction (<0.125mm)*

Predominant (>70%)

**Calcite:** Mostly found within the matrix. Light orange, pink color, <0.005mm, mode 0.005mm.

Few (5-15%)

**Opaque** (Red rim) Measurement typically less than 0.1mm. Typically well rounded, high sphericity, <0.12mm, mode 0.08mm. Contains reddish brown inclusions, and at times a red rim. Very few opaque minerals are square in shape.

*Coarse Fraction (>0.125mm)*

Dominant (50-70%)

**Plagioclase Feldspar:** Typically euhedral, subrounded and high sphericity. Albite twinning, <1.08mm, Mode in 0.38mm.

**Orthoclase Feldspar:** Typically euhedral, subrounded and high sphericity. Simple twinning, <0.38mm, Mode in 0.35mm.

**Trachyandesite rock fragment:** The rock is very weathered and contains fractures. The center spotting is smaller in size than the outline grains. The groundmass of this rock is brown in color and cloudy in appearance. It is very fine grained, and contains aphanitic grains in groundmass. The overall shape is subrounded with high sphericity. Mid-size rock fragment, <1.08mm, mode 0.7mm.
Rutile or Hematite? Found throughout rock fragment in different shapes: small thin veins, dots/ specks, rounded-high sphericity. However, it is too small to observe any additional details. Some of these inclusions are 0.3mm is size- Plagioclase Feldspar: Range of sizes: two 0.3mm ones found in rock fragment, rest are speckled and located throughout fragment. Mineral has albite twinning- Chloritic clay?: Yellow/Orange minerals within matrix. Alteration

mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint.

Other trachyandesite rock fragments have a finer sediment accumulated between minerals. Binder is dark (more binder than mineral grains). Some of the minerals are euhedral shaped, others are round shaped. Small rounded silica grains close to 0.10mm are found within the rock fragments. These radiate high order colors in XPL-Feldspar-Quartz-Biotite Mica-Opaque-Chlorite (inside rounded grains).

Frequent (30-50%)

**Andesite rock fragment:** Fragment appears to be Igneous that is being metamorphosed, with some alteration. Matrix is similar to the other rock fragment matrixes. It is brown, gray in color with very small white particles. Contains phenocrysts of feldspar, while others contain more phenocrysts of an altered mafic mineral. <1.8mm, Mode is 0.65mm.
Feldspar (weathered) - Epidote- Opaque minerals with red rim- Chloritic clay? Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint.

Other andesite rock fragments are more intrusive and contain interlocking minerals.
Calcite (weathered)- Epidote- Opaque minerals with red rim mostly 0.01mm in size- Chloritic clay?: Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint.

**Granite rock fragment:** These pyroclastic rocks contain interlocking grains, and almost no groundmass, except for the edges of the rock. Overall, shape is sub rounded, high sphericity. Some of the plagioclase feldspar grains within the rock fragment measure 0.6mm. <1.15mm, Mode is 0.65mm.
Plagioclase Feldspar- Rutile or Hematite? Found in minor amounts, look like veins- Opaque- Chlorite?: Very small, almost 0.025mm in

size. Faint green in PPL. High birefringence in XPL, but low relief. Small inclusion within the plagioclase feldspar.

**Quartz Monzonite Porphyry rock fragment:** Contains a vast quantity of mineral inclusions. Overall, it is plagioclase phenocryst (porphyries- fine grained rocks with large crystals) located within an altered groundmass, <1.73mm, Mode is 1.4mm.
Plagioclase Feldspar (spotty surface indicative of alteration, elongated, euhedral shape) - Quartz- Rutile or Hematite? Found in minor amounts. Veiny appearance. However, hard to detect due to how small the mineral grain is. - Opaque- Alteration of mafic minerals? Unable to determine. Very weathered and small. Yellow specs- Calcite grain (some have large calcite mineral) 0.7mm in size.

Common (15-30%)

**Rhyolite rock fragments:** Extrusive rock, containing phenocrysts of biotite and calcite. Moderate Relief. Overall well rounded with high sphericity. Matrix might be sparitic. More sand size particles. Matrix is mostly composed of gray and black specs, instead of brown specs like the other rocks. Some contain chlorite minerals altering to biotite. <0.95mm, Mode is 0.9mm.
Feldspar- chlorite- biotite- calcite; feldspar; Chlorite altering to biotite? Mineral is pleochroic, ranging from a very pale green to a brown green. It also appears to have a single plane of cleavage- opaque.

Few (5-15%)

**Calcite:** A majority of the calcite minerals are very weathered, and might be going through alteration. Usually, these are distinguishable from feldspar due to the differing cleavage planes. Most of these grains are euhedral shaped. Some of the calcite found has simple twinning. <0.5mm, mode is 0.37mm.

**Quartz:** Very hard to distinguish from feldspar since sample is so weathered. Typically euhedral, subrounded and high sphericity, <0.2mm, Mode is 0.175mm.

Very Few (2-5%)

**Igneous rock fragment?** Very weathered rock with only a few minerals, the rest is composed of very what appears to be a very weathered plagioclase feldspar. The rock fragment is distinguished by parallel lines across the fragment. More Intrusive than extrusive. Opaque minerals near the rock fragment but none located within the rock. <1.38mm, Mode is 0.8mm.

Quartz: too small to be able to differentiate. However, cleavage is not apparent- Feldspar: very weathered plagioclase feldspar with albite twinning- Biotite Mica: color increases with increasing Fe (iron content). Strong pleochroism: pale yellow to pale green to orange brown. Somewhat blotchy appearance- Chloritic clay? Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint.

Rare (0.5-2%)

**Biotite:** commonly found as long laths or euhedral shaped rectangles, 1 cleavage, pleochroism, some are 0.5 mm long and 0.02 mm thick. Some are a strong orange reddish color in PPL, <0.26mm, mode 0.20mm.

Very Rare (<0.5%)

**Epidote:** Mostly subrounded with low sphericity, <0.5mm, mode 0.35mm. More epidote is found within rock fragments, than as separate minerals.

**Opaque** (Red rim) typically well rounded, high sphericity, <0.6mm, no mode, average 0.34mm. Contains reddish brown inclusions, and at times a red rim.

**Sanidine Feldspar** Typically euhedral, subrounded and high sphericity, <0.4mm, Mode in 0.4mm.

**Muscovite?** Typically elongated. High birefringence colors, however grain is too small to define, <0.17mm, mode 0.15mm.

**Group 2: TUMA 25 (Exterior plaster sample)**

*Fine Fraction (<0.125mm)*

Predominant (>70%)

**Calcite:** Grains mostly found within the matrix. Light orange, pink color, <0.005mm, mode 0.005mm.

Frequent (30-50%)

**Quartz:** Some are subrounded with high sphericity and anhedral, <0.1mm, mode 0.07mm.

Common (15-30%)

**Epidote:** Smaller minerals of epidote found within gypsum finish. Subrounded with low to high sphericity in shape. Very high relief, <0.125mm, mode 0.035mm.

Few (5-15%)

**Opaque:** The opaque minerals have rutile or hematite in them, <0.085mm, mode 0.025mm.

Very Few (2-5%)

**Amphibole:** Pleochroism ranges light green to dark green. Less elongated than Biotite Mica. Initially the mineral appears to have a one plane cleavage but the angel at the edges suggests that it has two planes. It also is also subangular with low sphericity, and mostly euhedral, <0.075mm, mode 0.075mm.

Rare (0.5-2%)

**Biotite:** Has that characteristic red orange and yellow color as the biotite minerals observed in TUMA S-13. In PPL, it is pleochroic ranging from a deep yellow orange color to a brown red color, similar to oxidized minerals, <0.1mm, mode 0.1mm.

**Plagioclase Feldspar,** <0.125mm, mode 0.125mm.

**Chlorite:** Smaller minerals of chlorite found near epidote, <0.1mm, mode 0.1mm.

Very Rare (<0.5%)

**Alteration of mafic minerals?** Unable to determine. Very weathered and small. Yellow orange in both PPL and XPL. Moderate birefringence in XPL, moderate relief. Some look like laths, <0.125mm, mode 0.125mm.

*Coarse Fraction (>0.125mm)*

Dominant (50-70%)

**Quartz:** Some of the quartz observed are extremely weathered, and so it is hard to distinguish from calcite or feldspar. However, these did not show cleavage. Some are subrounded with high sphericity and anhedral, <0.5mm, mode 0.15mm.

**Trachyandesite rock fragments:** The rock fragment is light gray and dark brown, with a spotty appearance (PPL). It contains fractures. The center spotting is smaller in size than the outline grains. The groundmass of this rock is brown in color and cloudy in appearance. It is very fine grained, and contains aphanitic grains in groundmass. The overall shape is subrounded with high sphericity. <1.25mm, Mode is 1.25mm.

Micrite? Rounded grains, radiates high order colors in XPL. Cleavage is hard to detect, not a rhomb calcite either- Quartz- Plagioclase Feldspar- Rutile or Hematite? Found throughout rock fragment in different shapes: small thin veins, dots/ specks, and rounded-high sphericity. However, it is too small to observe any additional details- Chloritic clay? Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint- Biotite Mica (few mica inclusions): Angular, low sphericity, elongated.

**Andesite rock fragment:** Fragment appears to be Igneous that is being metamorphosed, with some alteration. Matrix is similar to the other rock fragment matrixes. It is brown, gray in color with small white grains. Some are elongated but some are more equant in shape within the matrix, <0.8mm, mode 0.75mm.

Feldspar-Quartz- Epidote- Opaque minerals with red rim- Chloritic clay? Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint- Biotite Mica (few mica inclusions): Angular, low sphericity, elongated.

Frequent (30-50%)

**Plagioclase Feldspar:** Typically euhedral, subrounded and high sphericity. Albite twinning, <0.625mm, Mode in 0.2mm.

Common (15-30%)

**Calcite:** A majority of the calcite minerals are very weathered, and might be going through alteration. Usually, these are distinguishable from feldspar due to the differing cleavage planes. Most of these grains are euhedral shaped, almost a perfect triangle or rectangle, <0.45mm, mode 0.225mm.

**Amphibolite rock fragment:** Subangular with low sphericity. Mostly composed of amphibole and quartz. Matrix is gray in color with very small fragments. Large phenocrysts of Quartz compose the Amphibolite rock fragment. Smaller inclusions of what appears to be amphibole are also found as well. Very few amphibolite rock fragments contain green specs in PPL, which are black in XPL, and are non pleochroic. These are two small to characterize. <1.125mm, mode 0.25mm.
Quartz- Amphibole- Green Specs?

Few (5-15%)

**Chloritic Clay Fine Grain rock fragment?** Subrounded with high sphericity. Deep yellow-orange-brown color in both XPL and PPL. No pleochroism. More of an intrusive rock, characterized by small inclusions. Radiating tones in lighter yellow mineral in XPL, <1.25mm, mode 0.625mm.

**Quartz Monzonite Porphyry: (Igneous Group)** Plagioclase phenocrysts (porphyries- fine grained rocks with large crystals) located within an altered groundmass. More of an aphanitic extrusive rock, <1.25mm, mode 0.25mm.
Plagioclase Feldspar- Quartz- Rutile or Hematite? Found in minor amounts. Veiny appearance. However, hard to detect due to how small the mineral grain is. - Opaque- Alteration of mafic minerals? Very weathered and small. Yellow specs- Calcite grain.

**Potassium Feldspar (Sanidine):** Very euhedral in shape. Two perfect planes of cleavage. Goes into extinction, but has no twinning. High Relief. <0.5mm, mode 0.45mm.

**Orthoclase Feldspar:** Typically euhedral, subrounded and high sphericity. Simple twinning, <0.25mm, mode 0.15mm.

**Igneous rock fragment?** Very weathered rock with only a few minerals, mostly composed of weathered plagioclase feldspar, <1mm, mode 0.35mm.

Feldspar, Quartz, Biotite Mica: color increases with increasing Fe (iron content). Strong pleochroism: pale yellow to pale green to orange brown-Chloritic clay? Yellow/Orange minerals within matrix. Alteration mineral, perhaps a micaceous clay. Or chlorite as a clay. Has a greenish tint.

Very Few (2-5%)

**Granite:** Pyroclastic rocks, interlocking grains, and almost no groundmass. This rock group appears to have an ultramafic composition. Overall shape is subrounded to subangular, low sphericity. Some of the plagioclase feldspar grains measuring 2mm within a 2mm fragment, <2.2mm, mode 1.5mm.

Plagioclase Feldspar (weathered) - Quartz- Rutile or Hematite: Found in minor amounts, look like veins- Opaque- Alteration of mafic minerals? Very weathered and small. Yellow specs. Moderate birefringence in XPL, moderate relief. Small inclusion within the matrix- Calcite

**Rhyolite:** Some are extremely weathered. Overall well rounded with high sphericity. Matrix might be sparitic. More sand size particles, <0.8mm, mode 0.25mm.

Feldspar- Chlorite altering to biotite- Biotite- Calcite- Opaque.

**Opaque:** (Red rim) typically well rounded, high sphericity. Contains reddish brown inclusions, and at times a red rim, <0.25mm, mode 0.2mm.

**Amphibole,** <0.625mm, mode 0.25mm.

**Chlorite,** <0.2mm, mode 0.15mm.

**Epidote:** Mostly subrounded with low sphericity, <0.25mm, mode 0.2mm.

Rare (0.5-2%)

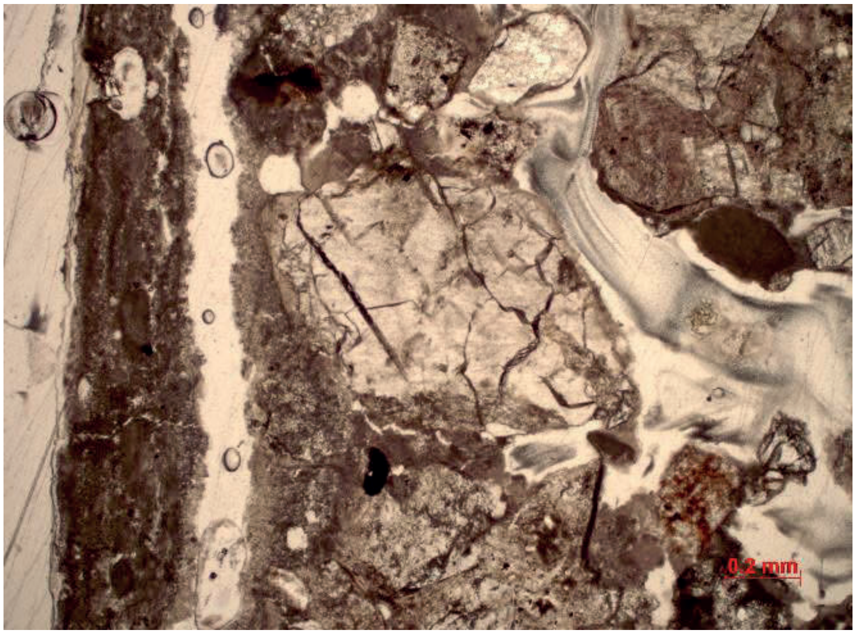
**Biotite:** commonly found as long laths or euhedral shaped rectangles, 1 cleavage, and pleochroism. Some are a strong orange reddish color in PPL, <1mm, mode 0.15mm.

Very Rare (<0.5%)

**Isotropic Mineral,** <0.2mm, mode 0.2mm.

## Photomicrographs:

## Group 1: TUMA S-13 (interior plaster sample)




**SAMPLE TUMA S-13**
**Thin Section (PPL)**

**ORIGIN**: Mission San José de Tumacácori, Tumacácori National Historic Park (Tucson, Arizona)
**RECEIVED**: January 2017

**IMAGING**: AxioVision Material Science Software for Research and Engineering

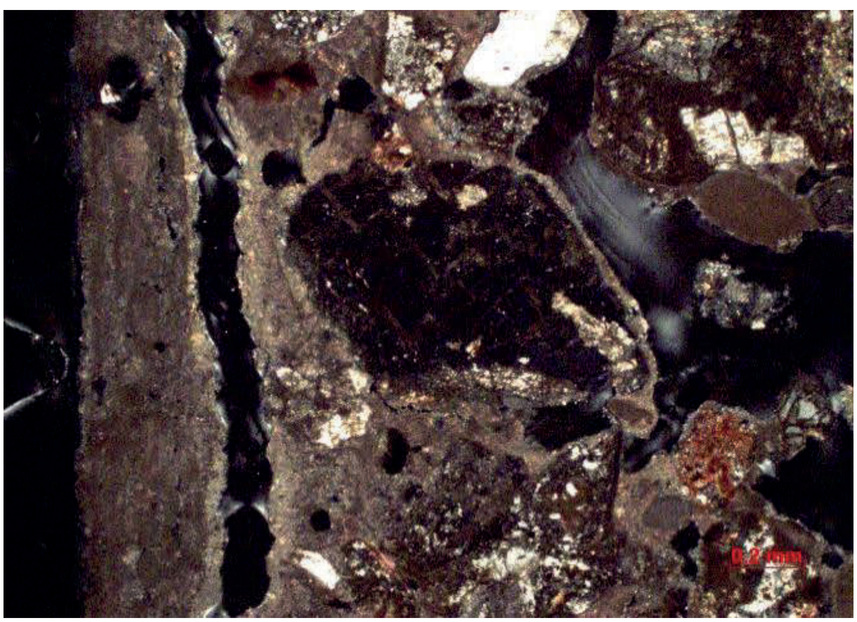
**MICROSCOPE**: Zeiss AX10

**OBJECTIVE**: 50 x
**ZOOM**: N/A

**TRINOCULAR MAG**: 1 x
**LIGHT SOURCE**: halogen

**FILTERS**: daylight
**COLOR TEMP**: N/A

Figure: Thin section of TUMA S-13 (PPL) obtained from the interior plaster of the Nave East Wall.




**SAMPLE TUMA S-13**
**Thin Section (XPL)**

**ORIGIN**: Mission San José de Tumacácori, Tumacácori National Historic Park (Tucson, Arizona)
**RECEIVED**: January 2017

**IMAGING**: AxioVision Material Science Software for Research and Engineering

**MICROSCOPE**: Zeiss AX10

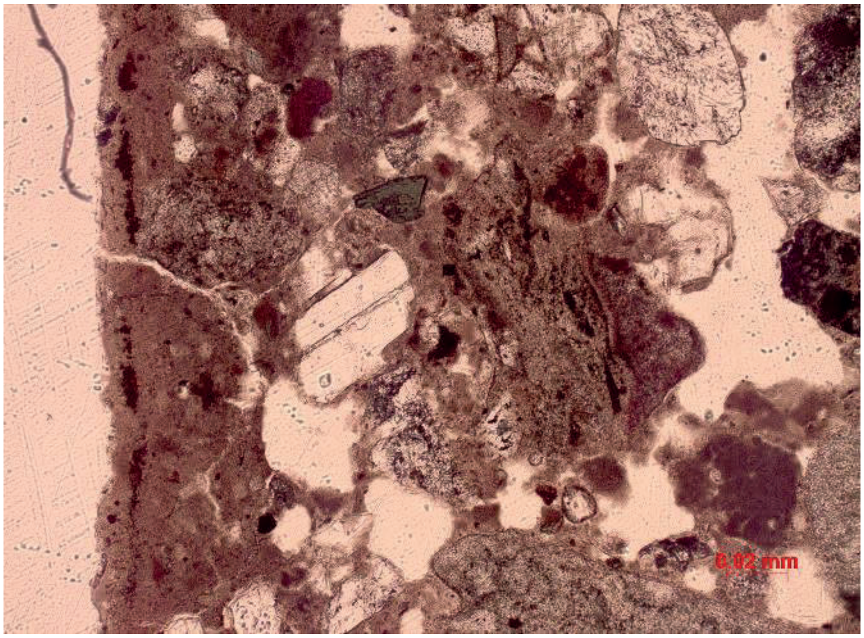
**OBJECTIVE**: 50 x
**ZOOM**: N/A

**TRINOCULAR MAG**: 1 x
**LIGHT SOURCE**: halogen

**FILTERS**: daylight
**COLOR TEMP**: N/A

Figure: Thin section of TUMA S-13 (XPL) obtained from the interior plaster of the Nave East Wall.

## Group 2: TUMA 25 (exterior plaster sample)




**SAMPLE TUMA 25**
**Thin Section (PPL)**

**ORIGIN**: Mission San José de Tumacácori, Tumacácori National Historic Park (Tucson, Arizona)
**RECEIVED**: April 2015

**IMAGING**: AxioVision Material Science Software for Research and Engineering

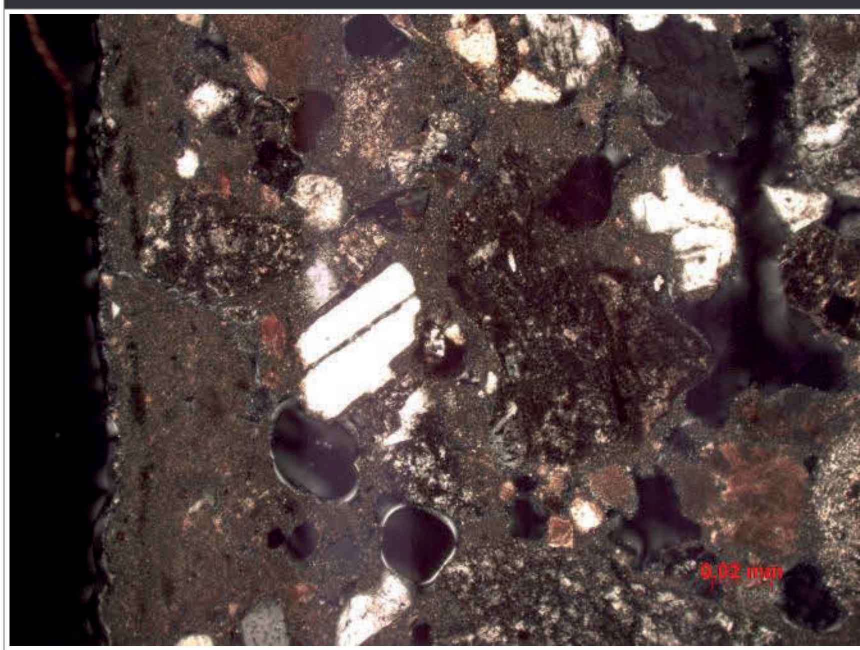
**MICROSCOPE**: Zeiss AX10

**OBJECTIVE**: 50 x
**ZOOM**: N/A

**TRINOCULAR MAG**: 1 x
**LIGHT SOURCE**: halogen

**FILTERS**: daylight
**COLOR TEMP**: N/A

Figure: Thin section of TUMA 25 (XPL) obtained from the exterior façade.




**SAMPLE TUMA S-25**
**Thin Section (XPL)**

**ORIGIN**: Mission San José de Tumacácori, Tumacácori National Historic Park (Tucson, Arizona)
**RECEIVED**: April 2015

**IMAGING**: AxioVision Material Science Software for Research and Engineering

**MICROSCOPE**: Zeiss AX10

**OBJECTIVE**: 50 x
**ZOOM**: N/A

**TRINOCULAR MAG**: 1 x
**LIGHT SOURCE**: halogen

**FILTERS**: daylight
**COLOR TEMP**: N/A

Figure: Thin section of TUMA 25 (XPL) obtained from the exterior façade.

## Appendix B: Characterization of Soils

Combined Wet and Dry Sieving Results

| | $M_{XT}$ (g) Weight of Sample | $M_{CT}$ (g) Weight of evaporating dish | $M_T$(g) Total weight of coarse particles | $M_{ST}$ (g) Weight of coarse soil particles | After Sieving | Margin of Error |
|---|---|---|---|---|---|---|
| ADOBE | 164.57 | 405.98 | 531.72 | 125.74 | 125.58 | 0.127247 |
| SOIL A | 154.46 | 369.7 | 478.17 | 108.47 | 108.4 | 0.064534 |
| SOIL B | 159.45 | 376.11 | 478.92 | 102.81 | 102.65 | 0.155627 |
| SOIL E | 153.73 | 372.53 | 456.54 | 84.01 | 83.94 | 0.083323 |

SOIL A

| SOIL A SIEVE TEST DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **ASTM Sieve Number** | **Screen Size (µm)** | **Mass of container (g)** | **Mass of sample & container (g)** | **Mass retained (g)** | **Percent mass retained** | **Percent on or above** | **Percent Passing** |
| | | $M_c$ | $M_2$ | $M_r$ ($M_2$ - $M_c$) | $\%M_r$ ($M_r$/$M_s$) *100% | $\%M_{rt}$ $\Sigma$ $\%M_r$ (on or above) | $\%M_{pt}$ 100% - $M_{rt}$% |
| **8** | 2360 | 2 | 12.09 | **10.09** | 9.31 | 9.31 | **90.69** |
| **16** | 1180 | 1.88 | 12.15 | **10.27** | 9.47 | 18.78 | **81.22** |
| **30** | 600 | 1.88 | 12.78 | **10.9** | 10.06 | 28.84 | **71.16** |
| **50** | 300 | 1.8 | 17.8 | **16** | 14.76 | 43.60 | **56.40** |
| **100** | 150 | 1.8 | 35.6 | **33.8** | 31.18 | 74.78 | **25.22** |
| **200** | 75 | 1.86 | 22.64 | **20.78** | 19.17 | 93.95 | **6.05** |
| **PAN** | 0 | 1.84 | 8.4 | **6.56** | 6.05 | 100.00 | **0.00** |
| | | | | **108.4** | 100 | | |

## SOIL B

| SOIL B SIEVE TEST DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| ASTM Sieve Number | Screen Size (µm) | Mass of container (g) | Mass of sample & container (g) | Mass retained (g) | Percent mass retained | Percent on or above | Percent Passing |
| | | $M_c$ | $M_2$ | $M_r$ $(M_2 - M_c)$ | $\%M_r$ $(M_r/M_s)$ *100% | $\%M_{rt}$ $\Sigma\ \%M_r$ (on or above) | $\%M_{pt}$ $100\% - M_{rt}\%$ |
| **8** | 2360 | 1.86 | 6.98 | **5.12** | 4.99 | 4.99 | **95.01** |
| **16** | 1180 | 1.85 | 8.46 | **6.61** | 6.44 | 11.43 | **88.57** |
| **30** | 600 | 2.12 | 12.40 | **10.28** | 10.01 | 21.44 | **78.56** |
| **50** | 300 | 2.11 | 25.04 | **22.93** | 22.34 | 43.78 | **56.22** |
| **100** | 150 | 2.04 | 36.19 | **34.15** | 33.27 | 77.05 | **22.95** |
| **200** | 75 | 1.95 | 18.88 | **16.93** | 16.49 | 93.54 | **6.46** |
| **PAN** | 0 | 1.85 | 8.48 | **6.63** | 6.46 | 100.00 | **0.00** |
| | | | | **102.65** | 100.00 | | |

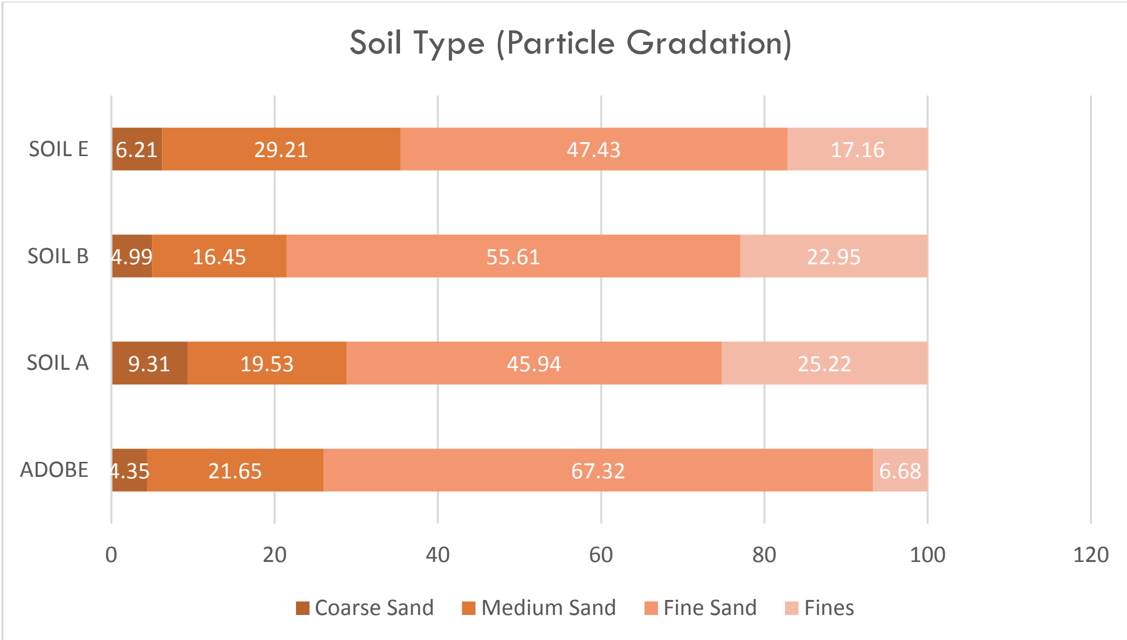
## SOIL E

| SOIL E SIEVE TEST DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| ASTM Sieve Number | Screen Size (µm) | Mass of container (g) | Mass of sample & container (g) | Mass retained (g) | Percent mass retained | Percent on or above | Percent Passing |
| | | $M_c$ | $M_2$ | $M_r$ $(M_2 - M_c)$ | $\%M_r$ $(M_r/M_s)$ *100% | $\%M_{rt}$ $\Sigma\ \%M_r$ (on or above) | $\%M_{pt}$ $100\% - M_{rt}\%$ |
| | 2360 | 1.96 | 7.17 | **5.21** | 6.21 | 6.21 | **93.79** |
| **16** | 1180 | 1.99 | 13.80 | **11.81** | 14.07 | 20.28 | **79.72** |
| **30** | 600 | 1.96 | 14.67 | **12.71** | 15.14 | 35.42 | **64.58** |
| **50** | 300 | 2.00 | 19.17 | **17.17** | 20.46 | 55.88 | **44.12** |
| **100** | 150 | 1.81 | 24.45 | **22.64** | 26.97 | 82.85 | **17.15** |
| **200** | 75 | 1.96 | 12.51 | **10.55** | 12.57 | 95.42 | **4.58** |
| **PAN** | 0 | 1.90 | 5.75 | **3.85** | 4.59 | 100.00 | **0.00** |
| | | | | **83.94** | 100.00 | | |

ADOBE

| ADOBE SIEVE TEST DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| ASTM Sieve Number | Screen Size (µm) | Mass of container (g) | Mass of sample & container (g) | Mass retained (g) | Percent mass retained | Percent on or above | Percent Passing |
| | | $M_c$ | $M_2$ | $M_r$ ($M_2$ - $M_c$) | $\%M_r$ ($M_r$ /$M_s$) *100% | $\%M_{rt}$ $\Sigma$ $\%M_r$ (on or above) | $\%M_{pt}$ 100% - $M_{rt}\%$ |
| **8** | *2360* | 1.82 | 7.28 | **5.46** | 4.35 | 4.35 | **95.65** |
| **16** | *1180* | 1.93 | 10.88 | **8.95** | 7.13 | 11.48 | **88.52** |
| **30** | *600* | 1.95 | 20.19 | **18.24** | 14.52 | 26.00 | **74.00** |
| **50** | *300* | 1.95 | 43.75 | **41.8** | 33.29 | 59.29 | **40.71** |
| **100** | *150* | 1.88 | 44.62 | **42.74** | 34.03 | 93.32 | **6.68** |
| **200** | *75* | 1.89 | 8.71 | **6.82** | 5.43 | 98.75 | **1.25** |
| **PAN** | *0* | 1.88 | 3.45 | **1.57** | 1.25 | 100.00 | **0.00** |
| | | | | **125.58** | 100.00 | | |

| | Coarse Sand | Medium Sand | Fine Sand | Fines | Total |
|---|---|---|---|---|---|
| ADOBE | 4.35 | 21.65 | 67.32 | 6.68 | 100.00 |
| SOIL A | 9.31 | 19.53 | 45.94 | 25.22 | 100.00 |
| SOIL B | 4.99 | 16.45 | 55.61 | 22.95 | 100.00 |
| SOIL E | 6.21 | 29.21 | 47.43 | 17.16 | 100.00 |


Soil Type (Particle Gradation)
SOIL E
6.21
29.21
47.43
17.16
SOIL B
4.99
16.45
55.61
22.95
SOIL A
9.31
19.53
45.94
25.22
ADOBE
4.35
21.65
67.32
6.68
0
20
40
60
80
100
120
Coarse Sand
Medium Sand
Fine Sand
Fines

| SOIL A | |
|---|---|
| Weight of beaker (g) | 200.62 |
| Total weight of sample (g) | 355.08 |
| Weight of the soil sample (g) | 154.46 |

| Date | Time of reading | Elapsed time (min) | Temp (C°) | Hydrometer Reading (Ra) | A | B | Meniscus Correction (Ra) | After Meniscus Correction (Rmc) | X (Dispersion Agent correction) | Ct | Corrected Reading (Rc) | a | Ws | % Finer of whole sample | Effective Depth (L) | L/t | K | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/24/2017 | 5:15 PM | 0.5 | 18 | 48 | 0 | 0.001 | 1 | 49 | 4.6 | -0.5 | 42.9 | 0.99 | 154.46 | 27.50 | 8.3 | 16.6 | 0.0138 | 4.07430976 | 4074.31 |
| 1/24/2017 | 5:16 PM | 1 | 18 | 47 | 0 | 0.001 | 1 | 48 | 4.6 | -0.5 | 41.9 | 0.99 | 154.46 | 26.86 | 8.4 | 8.4 | 0.0138 | 2.89827535 | 2898.28 |
| 1/24/2017 | 5:17 PM | 2 | 18 | 45 | 0 | 0.001 | 1 | 46 | 4.6 | -0.5 | 39.9 | 0.99 | 154.46 | 25.57 | 8.8 | 4.4 | 0.0138 | 2.0976177 | 2097.62 |
| 1/24/2017 | 5:19 PM | 4 | 18 | 43 | 0 | 0.001 | 1 | 44 | 4.6 | -0.5 | 37.9 | 0.99 | 154.46 | 24.29 | 9.1 | 2.275 | 0.0138 | 1.50831031 | 1508.31 |
| 1/24/2017 | 5:23 PM | 8 | 18 | 40 | 0 | 0.001 | 1 | 41 | 4.6 | -0.5 | 34.9 | 0.99 | 154.46 | 22.37 | 9.6 | 1.2 | 0.0138 | 1.09544512 | 1095.45 |
| 1/24/2017 | 5:30 PM | 15 | 18 | 37 | 0 | 0.001 | 1 | 38 | 4.6 | -0.5 | 31.9 | 0.99 | 154.46 | 20.45 | 10.1 | 0.673333333 | 0.0138 | 0.82056891 | 820.57 |
| 1/24/2017 | 5:45 PM | 30 | 18 | 34 | 0 | 0.001 | 1 | 35 | 4.6 | -0.5 | 28.9 | 0.99 | 154.46 | 18.52 | 10.5 | 0.35 | 0.0138 | 0.59160798 | 591.61 |
| 1/24/2017 | 6:15 PM | 60 | 18 | 30 | 0 | 0.001 | 1 | 31 | 4.6 | -0.5 | 24.9 | 0.99 | 154.46 | 15.96 | 11.2 | 0.186666667 | 0.0138 | 0.43204938 | 432.05 |
| 1/24/2017 | 7:15 PM | 120 | 18 | 26 | 0 | 0.001 | 1 | 27 | 4.6 | -0.5 | 20.9 | 0.99 | 154.46 | 13.40 | 11.9 | 0.099166667 | 0.0138 | 0.31490739 | 314.91 |
| 1/25/2017 | 3:00 PM | 1335 | 17 | 24 | 0 | 0.001 | 1 | 25 | 4.6 | -0.7 | 18.7 | 0.99 | 154.46 | 11.99 | 12.2 | 0.009138577 | 0.014 | 0.0955959 | 95.60 |
| 1/25/2017 | 6:00 PM | 1515 | 16 | 22 | 0 | 0.001 | 1 | 23 | 4.6 | -0.9 | 16.5 | 0.99 | 154.46 | 10.58 | 12.5 | 0.008250825 | 0.0141 | 0.09083405 | 90.83 |
| 1/26/2017 | 3:00 PM | 2775 | 17 | 21 | 0 | 0.001 | 1 | 22 | 4.6 | -0.7 | 15.7 | 0.99 | 154.46 | 10.06 | 12.7 | 0.004576577 | 0.014 | 0.0676504 | 67.65 |
| 1/26/2017 | 5:00 PM | 2895 | 17 | 21 | 0 | 0.001 | 1 | 22 | 4.6 | -0.7 | 15.7 | 0.99 | 154.46 | 10.06 | 12.7 | 0.004386874 | 0.014 | 0.06623348 | 66.23 |
| 1/26/2017 | 10:00 PM | 3195 | 17 | 20.5 | 0 | 0.001 | 1 | 21.5 | 4.6 | -0.7 | 15.2 | 0.99 | 154.46 | 9.74 | 12.8 | 0.00400626 | 0.014 | 0.06329502 | 63.30 |
| 1/27/2017 | 3:00 PM | 4215 | 17 | 20 | 0 | 0.001 | 1 | 21 | 4.6 | -0.7 | 14.7 | 0.99 | 154.46 | 9.42 | 12.9 | 0.003060498 | 0.014 | 0.05532177 | 55.32 |
| 1/27/2017 | 10:00 PM | 4635 | 16 | 20 | 0 | 0.001 | 1 | 21 | 4.6 | -0.9 | 14.5 | 0.99 | 154.46 | 9.29 | 12.9 | 0.002783172 | 0.0141 | 0.05275577 | 52.76 |
| 1/28/2017 | 3:00 PM | 5655 | 15.5 | 20 | 0 | 0.001 | 1 | 21 | 4.6 | -1 | 14.4 | 0.99 | 154.46 | 9.23 | 12.9 | 0.002281167 | 0.0146 | 0.04776157 | 47.76 |
| 1/30/2017 | 6:00 PM | 8715 | 15 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -1.1 | 13.3 | 0.99 | 154.46 | 8.52 | 13 | 0.001491681 | 0.0142 | 0.03862229 | 38.62 |
| 1/31/2017 | 10:00 PM | 10395 | 15 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -1.1 | 13.3 | 0.99 | 154.46 | 8.52 | 13 | 0.001250601 | 0.0142 | 0.03536384 | 35.36 |
| 2/2/2017 | 10:00 PM | 13275 | 16 | 20 | 0 | 0.001 | 1 | 21 | 4.6 | -0.9 | 14.5 | 0.99 | 154.46 | 9.29 | 12.9 | 0.000971751 | 0.0141 | 0.03117293 | 31.17 |
| 2/6/17 | 6:00 PM | 18795 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.9 | 13.5 | 0.99 | 154.46 | 8.65 | 13 | 0.000691673 | 0.0141 | 0.02629968 | 26.30 |
| 2/9/17 | 7:00 PM | 23175 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.9 | 13.5 | 0.99 | 154.46 | 8.65 | 13 | 0.000560949 | 0.0141 | 0.02368437 | 23.68 |
| 2/12/17 | 4:00 PM | 27315 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.9 | 13.5 | 0.99 | 154.46 | 8.65 | 13 | 0.000475929 | 0.0141 | 0.0218158 | 21.82 |
| 2/14/17 | 8:00 PM | 30435 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.9 | 13.5 | 0.99 | 154.46 | 8.65 | 13 | 0.00042714 | 0.0141 | 0.02066736 | 20.67 |
| 2/16/17 | 7:00 PM | 33255 | 17 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.7 | 13.2 | 0.99 | 154.46 | 8.46 | 13.1 | 0.000393926 | 0.0141 | 0.01984756 | 19.85 |
| 2/18/17 | 2:00 PM | 35835 | 16 | 19.5 | 0 | 0.001 | 1 | 20.5 | 4.6 | -0.9 | 14 | 0.99 | 154.46 | 8.97 | 12.95 | 0.000361379 | 0.0141 | 0.01900996 | 19.01 |
| 2/22/17 | 10:00 PM | 42075 | 19 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.3 | 14.1 | 0.99 | 154.46 | 9.04 | 13 | 0.000308972 | 0.0136 | 0.0175776 | 17.58 |
| 2/24/17 | 8:00 PM | 44835 | 21 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | 0.2 | 13.6 | 0.99 | 154.46 | 8.72 | 13.2 | 0.000294413 | 0.0133 | 0.01715846 | 17.16 |
| 2/27/17 | 9:00 PM | 49215 | 19 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000268211 | 0.0136 | 0.01637715 | 16.38 |
| 3/1/17 | 10:00 PM | 52155 | 19.5 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000253092 | 0.0139 | 0.01590886 | 15.91 |
| 3/4/17 | 8:00 PM | 56355 | 15 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.15 | 13.75 | 0.99 | 154.46 | 8.81 | 13.1 | 0.000232455 | 0.0142 | 0.01524647 | 15.25 |
| 3/7/17 | 11:00 PM | 60855 | 19 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000216909 | 0.0136 | 0.01472783 | 14.73 |
| 3/10/17 | 10:00 PM | 65115 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | 0 | 14.4 | 0.99 | 154.46 | 9.23 | 13 | 0.000199647 | 0.0141 | 0.01412964 | 14.13 |
| 3/13/17 | 8:00 PM | 69315 | 16 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.15 | 13.75 | 0.99 | 154.46 | 8.81 | 13.1 | 0.000188992 | 0.0141 | 0.01374745 | 13.75 |
| 3/15/17 | 11:00 PM | 72375 | 16 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.15 | 13.75 | 0.99 | 154.46 | 8.81 | 13.1 | 0.000181002 | 0.0141 | 0.01345369 | 13.45 |
| 3/17/17 | 10:00 PM | 75195 | 16.5 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.15 | 13.75 | 0.99 | 154.46 | 8.81 | 13.1 | 0.000174214 | 0.0145 | 0.013199 | 13.20 |
| 3/20/17 | 11:00 PM | 79455 | 17 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000166132 | 0.014 | 0.01288921 | 12.89 |
| 3/23/17 | 10:00 PM | 83715 | 16.5 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000157678 | 0.0145 | 0.01255698 | 12.56 |
| 3/26/17 | 3:00 PM | 87615 | 17.5 | 17.5 | 0 | 0.001 | 1 | 18.5 | 4.6 | -0.4 | 12.5 | 0.99 | 154.46 | 8.01 | 13.25 | 0.00015123 | 0.0139 | 0.01229755 | 12.30 |
| 3/29/17 | 7:00 PM | 92175 | 20 | 17 | 0 | 0.001 | 1 | 18 | 4.6 | -0.5 | 11.9 | 0.99 | 154.46 | 7.63 | 13.3 | 0.000144291 | 0.0134 | 0.01201211 | 12.01 |
| 4/2/17 | 6:00 PM | 97875 | 20 | 16 | 0 | 0.001 | 1 | 17 | 4.6 | -0.7 | 10.7 | 0.99 | 154.46 | 6.86 | 13.5 | 0.000137931 | 0.0134 | 0.0117444 | 11.74 |
| 4/5/17 | 7:00 PM | 102255 | 18 | 16 | 0 | 0.001 | 1 | 17 | 4.6 | -0.7 | 10.7 | 0.99 | 154.46 | 6.86 | 13.5 | 0.000132023 | 0.0138 | 0.01149012 | 11.49 |
| 4/9/17 | 7:00 PM | 108015 | 18 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000122205 | 0.0138 | 0.01105465 | 11.05 |
| 4/13/17 | 7:00 PM | 113775 | 20 | 18 | 0 | 0.001 | 1 | 19 | 4.6 | -0.3 | 13.1 | 0.99 | 154.46 | 8.40 | 13.2 | 0.000116018 | 0.0134 | 0.01077119 | 10.77 |
| 4/17/17 | 6:00 PM | 119475 | 22 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | 0.7 | 10.1 | 0.99 | 154.46 | 6.47 | 13.8 | 0.000115505 | 0.0131 | 0.01074734 | 10.75 |

| SOIL B | |
|---|---|
| Weight of beaker (g) | 264.68 |
| Total weight of sample (g) | 424.13 |
| Weight of the soil sample (g) | 159.45 |

| Date | ne of readi | psed time (m | Temp (C°) | ydrometer Reading (R | A | B | Meniscus Correction (Ra) | Meniscus (Corrected Reading) (Rmc) | X (Dispersion Agent correction) | Ct | Corrected Reading (Rc) | a | Ws | % Finer of whole sample | L | L/t | K | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/24/2017 | 5:15 PM | 0.5 | 18 | 59 | 0 | 0.001 | 1 | 60 | 4.6 | -0.5 | 53.9 | 0.99 | 159.45 | 33.80 | 6.6 | 13.2 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:16 PM | 1 | 18 | 57 | 0 | 0.001 | 1 | 58 | 4.6 | -0.5 | 51.9 | 0.99 | 159.45 | 32.55 | 7 | 7 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:17 PM | 2 | 18 | 56 | 0 | 0.001 | 1 | 57 | 4.6 | -0.5 | 50.9 | 0.99 | 159.45 | 31.92 | 7..1 | #VALUE! | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:19 PM | 4 | 18 | 54 | 0 | 0.001 | 1 | 55 | 4.6 | -0.5 | 48.9 | 0.99 | 159.45 | 30.67 | 7.4 | 1.85 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:23 PM | 8 | 18 | 52 | 0 | 0.001 | 1 | 53 | 4.6 | -0.5 | 46.9 | 0.99 | 159.45 | 29.41 | 7.8 | 0.975 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:30 PM | 15 | 18 | 49 | 0 | 0.001 | 1 | 50 | 4.6 | -0.5 | 43.9 | 0.99 | 159.45 | 27.53 | 8.3 | 0.553333333 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 5:45 PM | 30 | 18 | 44 | 0 | 0.001 | 1 | 45 | 4.6 | -0.5 | 38.9 | 0.99 | 159.45 | 24.40 | 9.1 | 0.303333333 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 6:15 PM | 60 | 18 | 41 | 0 | 0.001 | 1 | 42 | 4.6 | -0.5 | 35.9 | 0.99 | 159.45 | 22.51 | 9.6 | 0.16 | 0.0138 | 0.1174734 | 117.4734 |
| 1/24/2017 | 7:15 PM | 120 | 18 | 38 | 0 | 0.001 | 1 | 39 | 4.6 | -0.5 | 32.9 | 0.99 | 159.45 | 20.63 | 10.1 | 0.084166667 | 0.0138 | 0.1174734 | 117.4734 |
| 1/25/2017 | 3:00 PM | 1335 | 17 | 34 | 0 | 0.001 | 1 | 35 | 4.6 | -0.7 | 28.7 | 0.99 | 159.45 | 18.00 | 10.7 | 0.008014981 | 0.014 | 0.1183216 | 118.3216 |
| 1/25/2017 | 6:00 PM | 1515 | 16 | 31 | 0 | 0.001 | 1 | 32 | 4.6 | -0.9 | 25.5 | 0.99 | 159.45 | 15.99 | 11.2 | 0.007392739 | 0.0141 | 0.11874342 | 118.7434 |
| 1/26/2017 | 3:00 PM | 2775 | 17 | 29 | 0 | 0.001 | 1 | 30 | 4.6 | -0.7 | 23.7 | 0.99 | 159.45 | 14.86 | 11.5 | 0.004144144 | 0.014 | 0.1183216 | 118.3216 |
| 1/26/2017 | 5:00 PM | 2895 | 17 | 29 | 0 | 0.001 | 1 | 30 | 4.6 | -0.7 | 23.7 | 0.99 | 159.45 | 14.86 | 11.5 | 0.003972366 | 0.014 | 0.1183216 | 118.3216 |
| 1/26/2017 | 10:00 PM | 3195 | 17 | 28 | 0 | 0.001 | 1 | 29 | 4.6 | -0.7 | 22.7 | 0.99 | 159.45 | 14.24 | 11.7 | 0.003661972 | 0.014 | 0.1183216 | 118.3216 |
| 1/27/2017 | 3:00 PM | 4215 | 17 | 27.5 | 0 | 0.001 | 1 | 28.5 | 4.6 | -0.7 | 22.2 | 0.99 | 159.45 | 13.92 | 11.8 | 0.002799526 | 0.014 | 0.1183216 | 118.3216 |
| 1/27/2017 | 10:00 PM | 4635 | 16 | 27 | 0 | 0.001 | 1 | 28 | 4.6 | -0.9 | 21.5 | 0.99 | 159.45 | 13.48 | 11.9 | 0.002567422 | 0.0141 | 0.11874342 | 118.7434 |
| 1/28/2017 | 3:00 PM | 5655 | 15.5 | 27 | 0 | 0.001 | 1 | 28 | 4.6 | -1 | 21.4 | 0.99 | 159.45 | 13.42 | 11.9 | 0.002104332 | 0.0146 | 0.12083046 | 120.8305 |
| 1/30/2017 | 6:00 PM | 8715 | 15 | 26 | 0 | 0.001 | 1 | 27 | 4.6 | -1.1 | 20.3 | 0.99 | 159.45 | 12.73 | 12 | 0.001376936 | 0.0142 | 0.11916375 | 119.1638 |
| 1/31/2017 | 10:00 PM | 10395 | 15 | 25.5 | 0 | 0.001 | 1 | 26 | 4.6 | -1.1 | 19.8 | 0.99 | 159.45 | 12.42 | 12.1 | 0.001164021 | 0.0142 | 0.11916375 | 119.1638 |
| 2/2/2017 | 10:00 PM | 13275 | 16 | 23 | 0 | 0.001 | 1 | 24 | 4.6 | -0.9 | 17.5 | 0.99 | 159.45 | 10.98 | 12.5 | 0.00094162 | 0.0141 | 0.11874342 | 118.7434 |
| 2/6/17 | 6:00 PM | 18795 | 16 | 23 | 0 | 0.001 | 1 | 24 | 4.6 | -0.9 | 17.5 | 0.99 | 159.45 | 10.98 | 12.5 | 0.00066507 | 0.0141 | 0.11874342 | 118.7434 |
| 2/9/17 | 7:00 PM | 23175 | 16 | 21 | 0 | 0.001 | 1 | 22 | 4.6 | -0.9 | 15.5 | 0.99 | 159.45 | 9.72 | 12.9 | 0.000556634 | 0.0141 | 0.11874342 | 118.7434 |
| 2/12/17 | 4:00 PM | 27315 | 16 | 20 | 0 | 0.001 | 1 | 21 | 4.6 | -0.9 | 14.5 | 0.99 | 159.45 | 9.09 | 13 | 0.000475929 | 0.0141 | 0.11874342 | 118.7434 |
| 2/14/17 | 8:00 PM | 30435 | 16 | 17 | 0 | 0.001 | 1 | 18 | 4.6 | -0.9 | 11.5 | 0.99 | 159.45 | 7.21 | 13.5 | 0.000443568 | 0.0141 | 0.11874342 | 118.7434 |
| 2/16/17 | 7:00 PM | 33255 | 17 | 16 | 0 | 0.001 | 1 | 17 | 4.6 | -0.7 | 10.7 | 0.99 | 159.45 | 6.71 | 13.7 | 0.000411968 | 0.0141 | 0.11874342 | 118.7434 |
| 2/18/17 | 2:00 PM | 35835 | 16 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -0.9 | 8.5 | 0.99 | 159.45 | 5.33 | 14 | 0.00039068 | 0.0141 | 0.11874342 | 118.7434 |
| 2/22/17 | 10:00 PM | 42075 | 19 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.3 | 7.1 | 0.99 | 159.45 | 4.45 | 14.3 | 0.000339869 | 0.0136 | 0.11661904 | 116.619 |
| 2/24/17 | 8:00 PM | 44835 | 21 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | 0.2 | 7.1 | 0.99 | 159.45 | 4.45 | 14.4 | 0.000321178 | 0.0133 | 0.11532563 | 115.3256 |
| 2/27/17 | 9:00 PM | 49215 | 19 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 159.45 | 4.14 | 14.4 | 0.000292594 | 0.0136 | 0.11661904 | 116.619 |
| 3/1/17 | 10:00 PM | 52155 | 19.5 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 159.45 | 4.14 | 14.4 | 0.0002761 | 0.0139 | 0.11789826 | 117.8983 |
| 3/4/17 | 8:00 PM | 56355 | 15 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.15 | 7.25 | 0.99 | 159.45 | 4.55 | 14.3 | 0.000253749 | 0.0142 | 0.11916375 | 119.1638 |
| 3/7/17 | 11:00 PM | 60855 | 19 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 159.45 | 4.14 | 14.4 | 0.000236628 | 0.0136 | 0.11661904 | 116.619 |
| 3/10/17 | 10:00 PM | 65115 | 16 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | 0 | 6.4 | 0.99 | 159.45 | 4.01 | 14.5 | 0.000222683 | 0.0141 | 0.11874342 | 118.7434 |
| 3/13/17 | 8:00 PM | 69315 | 16 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.15 | 6.25 | 0.99 | 159.45 | 3.92 | 14.5 | 0.00020919 | 0.0141 | 0.11874342 | 118.7434 |
| 3/15/17 | 11:00 PM | 72375 | 16 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.15 | 6.25 | 0.99 | 159.45 | 3.92 | 14.5 | 0.000200345 | 0.0141 | 0.11874342 | 118.7434 |
| 3/17/17 | 10:00 PM | 75195 | 16.5 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.15 | 6.25 | 0.99 | 159.45 | 3.92 | 14.5 | 0.000192832 | 0.0145 | 0.12041595 | 120.4159 |
| 3/20/17 | 11:00 PM | 79455 | 17 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.3 | 6.1 | 0.99 | 159.45 | 3.83 | 14.5 | 0.000182493 | 0.014 | 0.1183216 | 118.3216 |
| 3/23/17 | 10:00 PM | 83715 | 16.5 | 10.5 | 0 | 0.001 | 1 | 11.5 | 4.6 | -0.3 | 5.6 | 0.99 | 159.45 | 3.51 | 14.6 | 0.000174401 | 0.0145 | 0.12041595 | 120.4159 |
| 3/26/17 | 3:00 PM | 87615 | 17.5 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | -0.4 | 5 | 0.99 | 159.45 | 3.14 | 14.7 | 0.000167779 | 0.0139 | 0.11789826 | 117.8983 |
| 3/29/17 | 7:00 PM | 92175 | 20 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | -0.5 | 4.9 | 0.99 | 159.45 | 3.07 | 14.7 | 0.000159479 | 0.0134 | 0.11575837 | 115.7584 |
| 4/2/17 | 6:00 PM | 97875 | 20 | 9.5 | 0 | 0.001 | 1 | 10.5 | 4.6 | -0.7 | 4.2 | 0.99 | 159.45 | 2.63 | 14.75 | 0.000150702 | 0.0134 | 0.11575837 | 115.7584 |
| 4/5/17 | 7:00 PM | 102255 | 18 | 9.5 | 0 | 0.001 | 1 | 10.5 | 4.6 | -0.7 | 4.2 | 0.99 | 159.45 | 2.63 | 14.75 | 0.000144247 | 0.0138 | 0.1174734 | 117.4734 |
| 4/9/17 | 7:00 PM | 108015 | 18 | 9 | 0 | 0.001 | 1 | 10 | 4.6 | -0.3 | 4.1 | 0.99 | 159.45 | 2.57 | 14.8 | 0.000137018 | 0.0138 | 0.1174734 | 117.4734 |
| 4/13/17 | 7:00 PM | 113775 | 20 | 9 | 0 | 0.001 | 1 | 10 | 4.6 | -0.3 | 4.1 | 0.99 | 159.45 | 2.57 | 14.8 | 0.000130081 | 0.0134 | 0.11575837 | 115.7584 |
| 4/17/17 | 6:00 PM | 119475 | 22 | 8 | 0 | 0.001 | 1 | 9 | 4.6 | 0.7 | 4.1 | 0.99 | 159.45 | 2.57 | 15 | 0.000125549 | 0.0131 | 0.11445523 | 114.4552 |

| SOIL E | |
|---|---|
| Weight of beaker (g) | 178.24 |
| Total weight of sample (g) | 331.97 |
| Weight of the soil sample (g) | 153.73 |

| Date | me of readi | psed time (m | Temp (C°) | ydrometer Reading (R | A | B | Meniscus Correction (Ra) | Meniscus (Corrected Reading) (Rmc) | X (Dispersion Agent correction) | Ct | Corrected Reading (Rc) | a | Ws | % Finer of whole sample | L | L/t | K | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/24/2017 | 5:15 PM | 0.5 | 18 | 64 | 0 | 0.001 | 1 | 65 | 4.6 | -0.5 | 58.9 | 0.99 | 153.73 | 38.31 | 5.9 | 11.8 | 0.0138 | 3.43511281 | 3435.113 |
| 1/24/2017 | 5:16 PM | 1 | 18 | 63 | 0 | 0.001 | 1 | 64 | 4.6 | -0.5 | 57.9 | 0.99 | 153.73 | 37.66 | 6 | 6 | 0.0138 | 2.44948974 | 2449.49 |
| 1/24/2017 | 5:17 PM | 2 | 18 | 60 | 0 | 0.001 | 1 | 61 | 4.6 | -0.5 | 54.9 | 0.99 | 153.73 | 35.71 | 6.5 | 3.25 | 0.0138 | 1.80277564 | 1802.776 |
| 1/24/2017 | 5:19 PM | 4 | 18 | 57 | 0 | 0.001 | 1 | 58 | 4.6 | -0.5 | 51.9 | 0.99 | 153.73 | 33.76 | 7 | 1.75 | 0.0138 | 1.32287566 | 1322.876 |
| 1/24/2017 | 5:23 PM | 8 | 18 | 55 | 0 | 0.001 | 1 | 56 | 4.6 | -0.5 | 49.9 | 0.99 | 153.73 | 32.46 | 7.3 | 0.9125 | 0.0138 | 0.95524866 | 955.2487 |
| 1/24/2017 | 5:30 PM | 15 | 18 | 52 | 0 | 0.001 | 1 | 53 | 4.6 | -0.5 | 46.9 | 0.99 | 153.73 | 30.51 | 7.8 | 0.52 | 0.0138 | 0.72111026 | 721.1103 |
| 1/24/2017 | 5:45 PM | 30 | 18 | 49 | 0 | 0.001 | 1 | 50 | 4.6 | -0.5 | 43.9 | 0.99 | 153.73 | 28.56 | 8.3 | 0.276666667 | 0.0138 | 0.52599113 | 525.9911 |
| 1/24/2017 | 6:15 PM | 60 | 18 | 46 | 0 | 0.001 | 1 | 47 | 4.6 | -0.5 | 40.9 | 0.99 | 153.73 | 26.61 | 8.8 | 0.146666667 | 0.0138 | 0.38297084 | 382.9708 |
| 1/24/2017 | 7:15 PM | 120 | 18 | 43 | 0 | 0.001 | 1 | 44 | 4.6 | -0.5 | 37.9 | 0.99 | 153.73 | 24.65 | 9.2 | 0.076666667 | 0.0138 | 0.27688746 | 276.8875 |
| 1/25/2017 | 3:00 PM | 1335 | 17 | 34 | 0 | 0.001 | 1 | 35 | 4.6 | -0.7 | 28.7 | 0.99 | 153.73 | 18.67 | 10.7 | 0.008014981 | 0.014 | 0.08952643 | 89.52643 |
| 1/25/2017 | 6:00 PM | 1515 | 16 | 31 | 0 | 0.001 | 1 | 32 | 4.6 | -0.9 | 25.5 | 0.99 | 153.73 | 16.59 | 11.2 | 0.007392739 | 0.0141 | 0.08598104 | 85.98104 |
| 1/26/2017 | 3:00 PM | 2775 | 17 | 29 | 0 | 0.001 | 1 | 30 | 4.6 | -0.7 | 23.7 | 0.99 | 153.73 | 15.42 | 11.5 | 0.004144144 | 0.014 | 0.06437503 | 64.37503 |
| 1/26/2017 | 5:00 PM | 2895 | 17 | 29 | 0 | 0.001 | 1 | 30 | 4.6 | -0.7 | 23.7 | 0.99 | 153.73 | 15.42 | 11.5 | 0.003972366 | 0.014 | 0.06302671 | 63.02671 |
| 1/26/2017 | 10:00 PM | 3195 | 17 | 28 | 0 | 0.001 | 1 | 29 | 4.6 | -0.7 | 22.7 | 0.99 | 153.73 | 14.77 | 11.7 | 0.003661972 | 0.014 | 0.06051423 | 60.51423 |
| 1/27/2017 | 3:00 PM | 4215 | 17 | 27 | 0 | 0.001 | 1 | 28 | 4.6 | -0.7 | 21.7 | 0.99 | 153.73 | 14.12 | 11.9 | 0.00282325 | 0.014 | 0.05313427 | 53.13427 |
| 1/27/2017 | 10:00 PM | 4635 | 16 | 26.5 | 0 | 0.001 | 1 | 27.5 | 4.6 | -0.9 | 21 | 0.99 | 153.73 | 13.66 | 11.95 | 0.002578209 | 0.0141 | 0.05077607 | 50.77607 |
| 1/28/2017 | 3:00 PM | 5655 | 15.5 | 26 | 0 | 0.001 | 1 | 27 | 4.6 | -1 | 20.4 | 0.99 | 153.73 | 13.27 | 12 | 0.002122016 | 0.0146 | 0.04606534 | 46.06534 |
| 1/30/2017 | 6:00 PM | 8715 | 15 | 25 | 0 | 0.001 | 1 | 26 | 4.6 | -1.1 | 19.3 | 0.99 | 153.73 | 12.55 | 12.2 | 0.001399885 | 0.0142 | 0.03741504 | 37.41504 |
| 1/31/2017 | 10:00 PM | 10395 | 15 | 24.5 | 0 | 0.001 | 1 | 25.5 | 4.6 | -1.1 | 18.8 | 0.99 | 153.73 | 12.23 | 12.3 | 0.001183261 | 0.0142 | 0.03439856 | 34.39856 |
| 2/2/2017 | 10:00 PM | 13275 | 16 | 23 | 0 | 0.001 | 1 | 24 | 4.6 | -0.9 | 17.5 | 0.99 | 153.73 | 11.38 | 12.5 | 0.00094162 | 0.0141 | 0.03068582 | 30.68582 |
| 2/6/17 | 6:00 PM | 18795 | 16 | 23 | 0 | 0.001 | 1 | 24 | 4.6 | -0.9 | 17.5 | 0.99 | 153.73 | 11.38 | 12.5 | 0.00066507 | 0.0141 | 0.02578896 | 25.78896 |
| 2/9/17 | 7:00 PM | 23175 | 16 | 22 | 0 | 0.001 | 1 | 23 | 4.6 | -0.9 | 16.5 | 0.99 | 153.73 | 10.73 | 12.7 | 0.000548004 | 0.0141 | 0.02340949 | 23.40949 |
| 2/12/17 | 4:00 PM | 27315 | 16 | 21 | 0 | 0.001 | 1 | 22 | 4.6 | -0.9 | 15.5 | 0.99 | 153.73 | 10.08 | 12.9 | 0.000472268 | 0.0141 | 0.02173173 | 21.73173 |
| 2/14/17 | 8:00 PM | 30435 | 16 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.9 | 13.5 | 0.99 | 153.73 | 8.78 | 13.2 | 0.000433711 | 0.0141 | 0.02082573 | 20.82573 |
| 2/16/17 | 7:00 PM | 33255 | 17 | 18.5 | 0 | 0.001 | 1 | 19.5 | 4.6 | -0.7 | 13.2 | 0.99 | 153.73 | 8.59 | 13.25 | 0.000398436 | 0.0141 | 0.01996087 | 19.96087 |
| 2/18/17 | 2:00 PM | 35835 | 16 | 17.5 | 0 | 0.001 | 1 | 18.5 | 4.6 | -0.9 | 12 | 0.99 | 153.73 | 7.81 | 13.4 | 0.000373936 | 0.0141 | 0.01933743 | 19.33743 |
| 2/22/17 | 10:00 PM | 42075 | 19 | 14.5 | 0 | 0.001 | 1 | 15.5 | 4.6 | -0.3 | 9.6 | 0.99 | 153.73 | 6.24 | 13.9 | 0.000330362 | 0.0136 | 0.01817588 | 18.17588 |
| 2/24/17 | 8:00 PM | 44835 | 21 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | 0.2 | 8.6 | 0.99 | 153.73 | 5.59 | 14.2 | 0.000316717 | 0.0133 | 0.01779654 | 17.79654 |
| 2/27/17 | 9:00 PM | 49215 | 19 | 12.5 | 0 | 0.001 | 1 | 13.5 | 4.6 | -0.3 | 7.6 | 0.99 | 153.73 | 4.94 | 14.25 | 0.000289546 | 0.0136 | 0.01701605 | 17.01605 |
| 3/1/17 | 10:00 PM | 52155 | 19.5 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.3 | 7.1 | 0.99 | 153.73 | 4.62 | 14.3 | 0.000274183 | 0.0139 | 0.01655846 | 16.55846 |
| 3/4/17 | 8:00 PM | 56355 | 15 | 12.5 | 0 | 0.001 | 1 | 13.5 | 4.6 | -0.15 | 7.75 | 0.99 | 153.73 | 5.04 | 14.25 | 0.000252861 | 0.0142 | 0.01590161 | 15.90161 |
| 3/7/17 | 11:00 PM | 60855 | 19 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 153.73 | 4.29 | 14.4 | 0.000236628 | 0.0136 | 0.01538272 | 15.38272 |
| 3/10/17 | 10:00 PM | 65115 | 16 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | 0 | 7.4 | 0.99 | 153.73 | 4.81 | 14.3 | 0.000219611 | 0.0141 | 0.01481929 | 14.81929 |
| 3/13/17 | 8:00 PM | 69315 | 16 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.15 | 7.25 | 0.99 | 153.73 | 4.72 | 14.3 | 0.000206305 | 0.0141 | 0.01436331 | 14.36331 |
| 3/15/17 | 11:00 PM | 72375 | 16 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.15 | 7.25 | 0.99 | 153.73 | 4.72 | 14.3 | 0.000197582 | 0.0141 | 0.01405639 | 14.05639 |
| 3/17/17 | 10:00 PM | 75195 | 16.5 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.15 | 6.75 | 0.99 | 153.73 | 4.39 | 14.4 | 0.000191502 | 0.0145 | 0.01383843 | 13.83843 |
| 3/20/17 | 11:00 PM | 79455 | 17 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 153.73 | 4.29 | 14.4 | 0.000181235 | 0.014 | 0.01346234 | 13.46234 |
| 3/23/17 | 10:00 PM | 83715 | 16.5 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.3 | 6.6 | 0.99 | 153.73 | 4.29 | 14.4 | 0.000172012 | 0.0145 | 0.01311534 | 13.11534 |
| 3/26/17 | 3:00 PM | 87615 | 17.5 | 11.5 | 0 | 0.001 | 1 | 12.5 | 4.6 | -0.4 | 6.5 | 0.99 | 153.73 | 4.23 | 14.4 | 0.000164355 | 0.0139 | 0.01282012 | 12.82012 |
| 3/29/17 | 7:00 PM | 92175 | 20 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.5 | 5.9 | 0.99 | 153.73 | 3.84 | 14.5 | 0.000157309 | 0.0134 | 0.01254231 | 12.54231 |
| 4/2/17 | 6:00 PM | 97875 | 20 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | -0.7 | 4.7 | 0.99 | 153.73 | 3.06 | 14.7 | 0.000150192 | 0.0134 | 0.01225527 | 12.25527 |
| 4/5/17 | 7:00 PM | 102255 | 18 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.7 | 5.7 | 0.99 | 153.73 | 3.71 | 14.5 | 0.000141802 | 0.0138 | 0.01190808 | 11.90808 |
| 4/9/17 | 7:00 PM | 108015 | 18 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | -0.3 | 5.1 | 0.99 | 153.73 | 3.32 | 14.7 | 0.000136092 | 0.0138 | 0.01166586 | 11.66586 |
| 4/13/17 | 7:00 PM | 113775 | 20 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | -0.3 | 5.1 | 0.99 | 153.73 | 3.32 | 14.7 | 0.000129202 | 0.0134 | 0.01136672 | 11.36672 |
| 4/17/17 | 6:00 PM | 119475 | 22 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | 0.7 | 6.1 | 0.99 | 153.73 | 3.97 | 14.7 | 0.000123038 | 0.0131 | 0.01109226 | 11.09226 |

| ADOBE | |
|---|---|
| Weight of beaker (g) | 215 |
| Total weight of sample (g) | 379.65 |
| Weight of the soil sample (g) | 164.57 |

| Date | ne of readi | psed time (m | Temp (C°) | ydrometer Reading (R | A | B | Meniscus Correction (Ra) | Meniscus (Corrected Reading) (Rmc) | X (Dispersion Agent correction) | Ct | Corrected Reading (Rc) | a | Ws | % Finer of whole sample | L | L/t | K | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/24/2017 | 5:15 PM | 0.5 | 18 | 38 | 0 | 0.001 | 1 | 39 | 4.6 | -0.5 | 32.9 | 0.99 | 164.57 | 19.99 | 10.1 | 20.2 | 0.0138 | 4.49444101 | 4494.441 |
| 1/24/2017 | 5:16 PM | 1 | 18 | 37 | 0 | 0.001 | 1 | 38 | 4.6 | -0.5 | 31.9 | 0.99 | 164.57 | 19.38 | 10.2 | 10.2 | 0.0138 | 3.19374388 | 3193.744 |
| 1/24/2017 | 5:17 PM | 2 | 18 | 36 | 0 | 0.001 | 1 | 37 | 4.6 | -0.5 | 30.9 | 0.99 | 164.57 | 18.78 | 10.4 | 5.2 | 0.0138 | 2.28035085 | 2280.351 |
| 1/24/2017 | 5:19 PM | 4 | 18 | 35 | 0 | 0.001 | 1 | 36 | 4.6 | -0.5 | 29.9 | 0.99 | 164.57 | 18.17 | 10.5 | 2.625 | 0.0138 | 1.62018517 | 1620.185 |
| 1/24/2017 | 5:23 PM | 8 | 18 | 33 | 0 | 0.001 | 1 | 34 | 4.6 | -0.5 | 27.9 | 0.99 | 164.57 | 16.95 | 10.9 | 1.3625 | 0.0138 | 1.16726175 | 1167.262 |
| 1/24/2017 | 5:30 PM | 15 | 18 | 31 | 0 | 0.001 | 1 | 32 | 4.6 | -0.5 | 25.9 | 0.99 | 164.57 | 15.74 | 11.2 | 0.746666667 | 0.0138 | 0.86409876 | 864.0988 |
| 1/24/2017 | 5:45 PM | 30 | 18 | 28 | 0 | 0.001 | 1 | 29 | 4.6 | -0.5 | 22.9 | 0.99 | 164.57 | 13.92 | 11.7 | 0.39 | 0.0138 | 0.6244998 | 624.4998 |
| 1/24/2017 | 6:15 PM | 60 | 18 | 25 | 0 | 0.001 | 1 | 26 | 4.6 | -0.5 | 19.9 | 0.99 | 164.57 | 12.09 | 12.2 | 0.203333333 | 0.0138 | 0.45092498 | 450.925 |
| 1/24/2017 | 7:15 PM | 120 | 18 | 23 | 0 | 0.001 | 1 | 24 | 4.6 | -0.5 | 17.9 | 0.99 | 164.57 | 10.88 | 12.5 | 0.104166667 | 0.0138 | 0.32274861 | 322.7486 |
| 1/25/2017 | 3:00 PM | 1335 | 17 | 19 | 0 | 0.001 | 1 | 20 | 4.6 | -0.7 | 13.7 | 0.99 | 164.57 | 8.32 | 13.2 | 0.00988764 | 0.014 | 0.09943662 | 99.43662 |
| 1/25/2017 | 6:00 PM | 1515 | 16 | 17 | 0 | 0.001 | 1 | 18 | 4.6 | -0.9 | 11.5 | 0.99 | 164.57 | 6.99 | 13.5 | 0.008910891 | 0.0141 | 0.09439752 | 94.39752 |
| 1/26/2017 | 3:00 PM | 2775 | 17 | 15.5 | 0 | 0.001 | 1 | 16.5 | 4.6 | -0.7 | 10.2 | 0.99 | 164.57 | 6.20 | 13.9 | 0.005009009 | 0.014 | 0.07077435 | 70.77435 |
| 1/26/2017 | 5:00 PM | 2895 | 17 | 15.5 | 0 | 0.001 | 1 | 16.5 | 4.6 | -0.7 | 10.2 | 0.99 | 164.57 | 6.20 | 13.9 | 0.004801382 | 0.014 | 0.069292 | 69.292 |
| 1/26/2017 | 10:00 PM | 3195 | 17 | 15 | 0 | 0.001 | 1 | 16 | 4.6 | -0.7 | 9.7 | 0.99 | 164.57 | 5.89 | 13.8 | 0.004319249 | 0.014 | 0.06572099 | 65.72099 |
| 1/27/2017 | 3:00 PM | 4215 | 17 | 15 | 0 | 0.001 | 1 | 16 | 4.6 | -0.7 | 9.7 | 0.99 | 164.57 | 5.89 | 13.8 | 0.003274021 | 0.014 | 0.05721906 | 57.21906 |
| 1/27/2017 | 10:00 PM | 4635 | 16 | 15 | 0 | 0.001 | 1 | 16 | 4.6 | -0.9 | 9.5 | 0.99 | 164.57 | 5.77 | 13.8 | 0.002977346 | 0.0141 | 0.05456506 | 54.56506 |
| 1/28/2017 | 3:00 PM | 5655 | 15.5 | 15 | 0 | 0.001 | 1 | 16 | 4.6 | -1 | 9.4 | 0.99 | 164.57 | 5.71 | 13.8 | 0.002440318 | 0.0146 | 0.04939958 | 49.39958 |
| 1/30/2017 | 6:00 PM | 8715 | 15 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -1.1 | 8.3 | 0.99 | 164.57 | 5.04 | 14 | 0.001606426 | 0.0142 | 0.04008024 | 40.08024 |
| 1/31/2017 | 10:00 PM | 10395 | 15 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -1.1 | 8.3 | 0.99 | 164.57 | 5.04 | 14 | 0.001346801 | 0.0142 | 0.03669879 | 36.69879 |
| 2/2/2017 | 10:00 PM | 13275 | 16 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -0.9 | 8.5 | 0.99 | 164.57 | 5.16 | 14 | 0.001054614 | 0.0141 | 0.03247482 | 32.47482 |
| 2/6/17 | 6:00 PM | 18795 | 16 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -0.9 | 8.5 | 0.99 | 164.57 | 5.16 | 14 | 0.000744879 | 0.0141 | 0.02729247 | 27.29247 |
| 2/9/17 | 7:00 PM | 23175 | 16 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -0.9 | 8.5 | 0.99 | 164.57 | 5.16 | 14 | 0.000604099 | 0.0141 | 0.02457843 | 24.57843 |
| 2/12/17 | 4:00 PM | 27315 | 16 | 14 | 0 | 0.001 | 1 | 15 | 4.6 | -0.9 | 8.5 | 0.99 | 164.57 | 5.16 | 14 | 0.000512539 | 0.0141 | 0.02263932 | 22.63932 |
| 2/14/17 | 8:00 PM | 30435 | 16 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.9 | 8 | 0.99 | 164.57 | 4.86 | 14.1 | 0.000463282 | 0.0141 | 0.021524 | 21.524 |
| 2/16/17 | 7:00 PM | 33255 | 17 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.7 | 8.2 | 0.99 | 164.57 | 4.98 | 14.1 | 0.000423996 | 0.0141 | 0.02059117 | 20.59117 |
| 2/18/17 | 2:00 PM | 35835 | 16 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.9 | 8 | 0.99 | 164.57 | 4.86 | 14.1 | 0.00039347 | 0.0141 | 0.01983608 | 19.83608 |
| 2/22/17 | 10:00 PM | 42075 | 19 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.3 | 8.1 | 0.99 | 164.57 | 4.92 | 14.2 | 0.000337493 | 0.0136 | 0.01837097 | 18.37097 |
| 2/24/17 | 8:00 PM | 44835 | 21 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | 0.2 | 8.6 | 0.99 | 164.57 | 5.23 | 14.2 | 0.000316717 | 0.0133 | 0.01779654 | 17.79654 |
| 2/27/17 | 9:00 PM | 49215 | 19 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.3 | 8.1 | 0.99 | 164.57 | 4.92 | 14.2 | 0.00028853 | 0.0136 | 0.01698617 | 16.98617 |
| 3/1/17 | 10:00 PM | 52155 | 19.5 | 12.5 | 0 | 0.001 | 1 | 13.5 | 4.6 | -0.3 | 7.6 | 0.99 | 164.57 | 4.62 | 14.25 | 0.000273224 | 0.0139 | 0.01652949 | 16.52949 |
| 3/4/17 | 8:00 PM | 56355 | 15 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.15 | 8.75 | 0.99 | 164.57 | 5.32 | 14.1 | 0.0002502 | 0.0142 | 0.0158177 | 15.8177 |
| 3/7/17 | 11:00 PM | 60855 | 19 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.3 | 8.1 | 0.99 | 164.57 | 4.92 | 14.2 | 0.000233342 | 0.0136 | 0.01527552 | 15.27552 |
| 3/10/17 | 10:00 PM | 65115 | 16 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | 0 | 8.9 | 0.99 | 164.57 | 5.41 | 14.1 | 0.00021654 | 0.0141 | 0.0147153 | 14.7153 |
| 3/13/17 | 8:00 PM | 69315 | 16 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.15 | 8.75 | 0.99 | 164.57 | 5.32 | 14.1 | 0.000203419 | 0.0141 | 0.01426251 | 14.26251 |
| 3/15/17 | 11:00 PM | 72375 | 16 | 13.5 | 0 | 0.001 | 1 | 14.5 | 4.6 | -0.15 | 8.75 | 0.99 | 164.57 | 5.32 | 14.1 | 0.000194819 | 0.0141 | 0.01395775 | 13.95775 |
| 3/17/17 | 10:00 PM | 75195 | 16.5 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.15 | 8.25 | 0.99 | 164.57 | 5.01 | 14.2 | 0.000188842 | 0.0145 | 0.01374199 | 13.74199 |
| 3/20/17 | 11:00 PM | 79455 | 17 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.3 | 8.1 | 0.99 | 164.57 | 4.92 | 14.2 | 0.000178718 | 0.014 | 0.01336853 | 13.36853 |
| 3/23/17 | 10:00 PM | 83715 | 16.5 | 13 | 0 | 0.001 | 1 | 14 | 4.6 | -0.3 | 8.1 | 0.99 | 164.57 | 4.92 | 14.2 | 0.000169623 | 0.0145 | 0.01302394 | 13.02394 |
| 3/26/17 | 3:00 PM | 87615 | 17.5 | 12.5 | 0 | 0.001 | 1 | 13.5 | 4.6 | -0.4 | 7.5 | 0.99 | 164.57 | 4.56 | 14.25 | 0.000162643 | 0.0139 | 0.01275317 | 12.75317 |
| 3/29/17 | 7:00 PM | 92175 | 20 | 12 | 0 | 0.001 | 1 | 13 | 4.6 | -0.5 | 6.9 | 0.99 | 164.57 | 4.19 | 14.3 | 0.00015514 | 0.0134 | 0.01245551 | 12.45551 |
| 4/2/17 | 6:00 PM | 97875 | 20 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.7 | 5.7 | 0.99 | 164.57 | 3.46 | 14.5 | 0.000148148 | 0.0134 | 0.01217161 | 12.17161 |
| 4/5/17 | 7:00 PM | 102255 | 18 | 11 | 0 | 0.001 | 1 | 12 | 4.6 | -0.7 | 5.7 | 0.99 | 164.57 | 3.46 | 14.5 | 0.000141802 | 0.0138 | 0.01190808 | 11.90808 |
| 4/9/17 | 7:00 PM | 108015 | 18 | 10.5 | 0 | 0.001 | 1 | 11.5 | 4.6 | -0.3 | 5.6 | 0.99 | 164.57 | 3.40 | 14.6 | 0.000135166 | 0.0138 | 0.01162611 | 11.62611 |
| 4/13/17 | 7:00 PM | 113775 | 20 | 10.5 | 0 | 0.001 | 1 | 11.5 | 4.6 | -0.3 | 5.6 | 0.99 | 164.57 | 3.40 | 14.6 | 0.000128323 | 0.0134 | 0.01132799 | 11.32799 |
| 4/17/17 | 6:00 PM | 119475 | 22 | 10 | 0 | 0.001 | 1 | 11 | 4.6 | 0.7 | 6.1 | 0.99 | 164.57 | 3.71 | 14.7 | 0.000123038 | 0.0131 | 0.01109226 | 11.09226 |

## Appendix C: Grout Rheology Calculations

- **Flow/ Viscosity**

Batch #1 was prepared on 03/01/2017.
Batch #2 was prepared on 03/15/2017.

| **Surrounding Conditions** | Batch 1 | Batch 2 |
|---|---|---|
| Room Temperature (°C) | 22.2 | 18.9 |
| Relative Humidity (%) | 44 | 23 |

| **Temperature Reading** | Batch 1 | Batch 2 |
|---|---|---|
| Mixing water (°C) | 18 | 16.5 |
| Grout (°C) | 22 | 23 |

| **Duration of mixing** | Time |
|---|---|
| Batch 1 | 5 min |
| Batch 2 | 5 min |

| **Time of efflux of grout** | Batch 1 | Batch 2 | |
|---|---|---|---|
| Reading #1 (s) | 14.28 | 20.84 | |
| Reading #2 (s) | 16.05 | 22.62 | |
| Average Reading (s) | 15.165 | 21.73 | **18.4475** |

| **Time of efflux of water** | Batch 1 | Batch 2 | |
|---|---|---|---|
| Reading #1 (s) | 5.72 | 4.46 | |
| Reading #2 (s) | 3.98 | 3.89 | |
| Average Reading (s) | 4.85 | 4.175 | **4.5125** |

- **Wet Density**

*2.3. Part I Laboratory Testing Procedure* (GCI 2011, 21):[87]

The wet density value (lab testing) was calculated using the following formulas:

$$\rho_{wet} = \frac{M_g}{400}$$

$$M_g = M_t - M_0$$

$M_0$(g): Weight of the cup

[87] Performed on March 2, 2017.

$M_t$(g): Total weight of the grout and cup
$M_g$(g): Weight of the grout
$\rho_{wet}$ ($g \times cm^{-3}$): Wet density of the grout

| Specimen | Weight of the cup (g) | Weight of the grout + cup (g) | Weight of the grout (g) | Wet density of grout (g*cm–3 ) |
|---|---|---|---|---|
| 1 | 98.63 | 1662.78 | 1564.15 | 1.84 |
| 2 | 101.3 | 1684.25 | 1582.95 | 1.86 |

4.5. *Part II Field Testing Procedures* (GCI 2011, 81):[88]

The wet density value (field testing) was calculated using the following formula:

*Used a 12ml syringe, instead of a 5ml syringe.

$$\rho_{wet} = \frac{M_g}{12}$$

$M_g$(g): Weight of the grout
$\rho_{wet}$ ($g \times cm^{-3}$): Wet density of the grout

| Specimen | Weight of 12mL syringe (g) | Weight of the grout + syringe (g) | Weight of the grout in syringe (g) | Wet density of grout (g*cm–3 ) |
|---|---|---|---|---|
| 1 | 4.9 | 27.4 | 22.5 | 1.88 |
| 2 | 6.3 | 29.1 | 22.8 | 1.90 |

- **Drying Shrinkage** (ASTM C1148-92a)

The percent shrinkage, S, of the six specimens was calculated using the following formula:

$$S = \left[\frac{(L_1 - L}{L_0}\right] \times 100$$

Where:

L0 = effective gage length, cm (in.),

L1 = initial measurement after removal from moist cure, cm, (in.), and

L = measurement during or after drying, cm (in.)

88 Performed on March 15, 2017.

| Grout Name | TUMA Soil Grout |
|---|---|
| **Grout Proportions** | 2.5: 1 (solid to water) |
| **Operator** | Nicole Declet |
| **Date** | 02/14/2017 |

*A length comparator as specified in the ASTM was used to measure the prisms.

| **Specimen (prism)** | **Effective gage length L0 (in.)** | **4 days** Initial measurement after removal L1 (in.) | **11 days** Measurement during drying L (in.) | **18 days** | **25 days** | Drying Shrinkage Average mean | Percent Shrinkage (S) |
|---|---|---|---|---|---|---|---|
| 1 | 5.438 | 7.646 | 5.41 | 5.344 | 5.372 | 5.943 | 41.82 |
| 2 | 5.438 | 6.04 | 4.584 | 4.532 | 4.554 | 4.9275 | 27.33 |
| 3 | 5.438 | 6.478 | 5.096 | 5.062 | 5.068 | 5.426 | 25.93 |
| 4 | 5.438 | 4.786 | 2.632 | 2.59 | 2.618 | 3.1565 | 39.87 |
| 5 | 5.438 | 6.758 | 5.862 | 5.82 | 5.83 | 6.0675 | 17.07 |
| 6 | 5.438 | 9.62 | 8.314 | 8.28 | 8.29 | 8.626 | 24.46 |

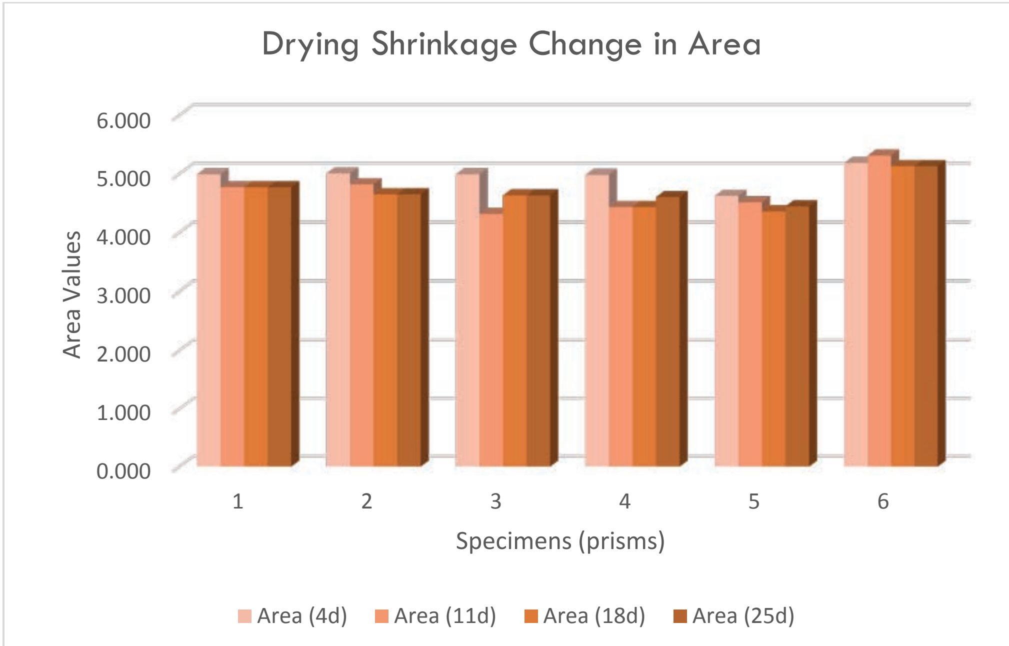
*Results that were less than 20% different from the average are shown in yellow.

The length, width and height for each prism was calculated every 4, 11, 18, and 25 days.

| Specimen (prism) | **4 days** | | | | **11 days** | | | |
|---|---|---|---|---|---|---|---|---|
| | Length (in) | Width (in) | Height (in) | **Area** | Length (in) | Width (in) | Height (in) | **Area** |
| 1 | 0.938 | 0.906 | 5.875 | **4.993** | 0.938 | 0.875 | 5.813 | **4.771** |
| 2 | 0.969 | 0.875 | 5.906 | **5.008** | 0.938 | 0.875 | 5.875 | **4.822** |
| 3 | 0.938 | 0.906 | 5.875 | **4.993** | 0.844 | 0.875 | 5.844 | **4.316** |
| 4 | 0.969 | 0.875 | 5.875 | **4.981** | 0.938 | 0.813 | 5.813 | **4.433** |
| 5 | 0.938 | 0.844 | 5.844 | **4.627** | 0.938 | 0.828 | 5.813 | **4.515** |
| 6 | 0.969 | 0.90625 | 5.906 | **5.186** | 0.969 | 0.938 | 5.844 | **5.312** |

| Specimen (prism) | **18 days** | | | | **25 days** | | | |
|---|---|---|---|---|---|---|---|---|
| | Length (in) | Width (in) | Height (in) | **Area** | Length (in) | Width (in) | Height (in) | **Area** |
| 1 | 0.938 | 0.875 | 5.813 | **4.771** | 0.938 | 0.875 | 5.813 | **4.771** |
| 2 | 0.938 | 0.844 | 5.875 | **4.651** | 0.938 | 0.844 | 5.875 | **4.651** |
| 3 | 0.906 | 0.875 | 5.844 | **4.633** | 0.906 | 0.875 | 5.844 | **4.633** |
| 4 | 0.938 | 0.813 | 5.813 | **4.433** | 0.938 | 0.844 | 5.813 | **4.602** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.906 | 0.828 | 5.813 | **4.361** | 0.906 | 0.844 | 5.813 | **4.445** |
| 6 | 0.969 | 0.906 | 5.844 | **5.131** | 0.969 | 0.906 | 5.844 | **5.131** |




- **Expansion & Bleeding** *2.2. Part I Laboratory Testing Procedure* (GCI 2011, 18):

The following formulas are used to calculate the Expansion and Bleeding of the grout:

$$\text{Expansion, E (\%)} = \frac{V_g - V_0}{V_0} \times 100$$

$$\text{Bleeding, B (\%)} = \frac{V_t - V_g}{V_0} \times 100$$

$$\text{Combined expansion, CE (\%)} = \frac{V_t - V_0}{V_0} \times 100$$

$$\text{Final Bleeding, FB (\%)} = \frac{V_w}{V_0} \times 100$$

$V_0$ (mL): Volume of the sample at the beginning of the test

$V_t$ (mL): Volume of the sample at prescribed intervals, measured at the upper surface of water layer

$V_g$ (mL): Volume of grout portion of sample at prescribed intervals, measured at the upper surface of grout

$V_w$ (mL): Volume of decanted bleed water

| **Grout Name** | TUMA Soil Grout | **Temperature (C°)** | 21 |
|---|---|---|---|
| **Grout Proportions** | 2.5: 1 (solid to water) | **Date** | 3/2/2017 |
| **Operator** | Nicole Declet | **Room** | ACL Laboratory |

| Time | Interval | Volume of sample (upper surface of water layer) (mL) | Volume of grout portion (upper surface of grout) (mL) | Expansion % | Combined Expansion % | Bleeding Expansion |
|---|---|---|---|---|---|---|
| 3:52:00 PM | 0.15 | 400 | 400 | 0 | 0 | 0 |
| 4:07:00 PM | 0.3 | 400 | 400 | 0 | 0 | 0 |
| 4:22:00 PM | 0.45 | 400 | 400 | 0 | 0 | 0 |
| 4:37:00 PM | 1 | 400 | 400 | 0 | 0 | 0 |
| 5:37:00 PM | 2 | 400 | 400 | 0 | 0 | 0 |
| 6:37:00 PM | 3 | 400 | 400 | 0 | 0 | 0 |
| 7:37:00 PM | 4 | 400 | 400 | 0 | 0 | 0 |
| 8:37:00 PM | 5 | 400 | 400 | 0 | 0 | 0 |
| 9:37:00 PM | 6 | 400 | 400 | 0 | 0 | 0 |
| 10:37:00 PM | 7 | 400 | 400 | 0 | 0 | 0 |
| 11:37:00 PM | 8 | 400 | 400 | 0 | 0 | 0 |

| | |
|---|---|
| Volume of sample at the beginning of test (mL) | 400 |
| Volume of decanted bleed water | 0 |
| Final Bleeding | 0 |

- **Splitting Tensile Strength** *2.5.Part I Laboratory Testing Procedure* (GCI 2011, 28):

The following formula was used to calculate the splitting tensile strength:

$$f = \frac{2 \times F}{\pi \times d \times l}$$

Where:

F (N): Breaking Load

d (mm): Specimen diameter

l (mm): Specimen length

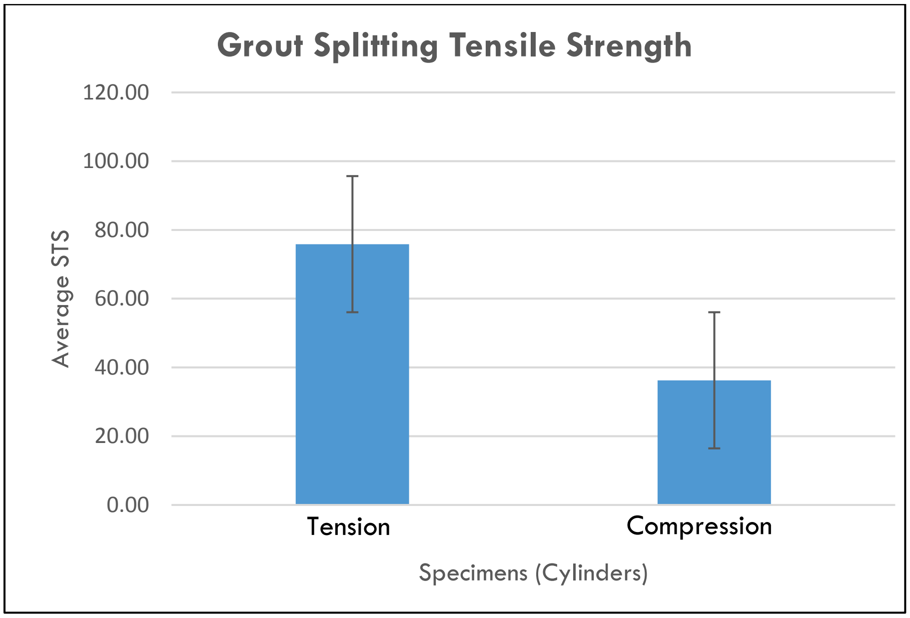
f ($N \times mm^{-2}$): Splitting Tensile Strength

| **Grout Name** | TUMA Soil Grout | **Age of specimen (days)** | 42 days |
|---|---|---|---|
| **Grout Proportions** | 2.5: 1 (solid to water) | **Date** | April 6, 2017. |
| **Operator** | Nicole Declet | | |

| Specimen | Length of specimen | Diameter of specimen | Breaking Load Total Maximum Load in lbf | Area of loaded surface in² | Compressive Strength in psi | Compressive Strength in psi (f(N*mm-2)) | Splitting Tensile Strength in psi | Splitting Tensile Strength (f(N*mm-2)) | Notes: |
|---|---|---|---|---|---|---|---|---|---|
| STS 2 | 3.806 | 1.8945 | 848.59 | 28.27580087 | 30.01117471 | 0.207 | 74.96091234 | 0.517 | 200 lbs/v 0.02 in/v |
| STS 4 | 3.8285 | 1.898 | 994.53 | 28.4725623 | 34.92941694 | 0.241 | 87.17528507 | 0.601 | 200 lbs/v 0.02 in/v |
| STS 7 | 3.7005 | 1.892 | 1040.12 | 27.60429892 | 37.67963834 | 0.26 | 94.6242073 | 0.652 | 200 lbs/v 0.02 in/v |
| STS 9 | 3.7805 | 1.885 | 1000.04 | 27.9549647 | 35.77325211 | 0.247 | 89.38345178 | 0.582 | 200 lbs/v 0.02 in/v |
| STS 10 | 3.7725 | 1.892 | 733.4 | 28.03204228 | 26.16291716 | 0.18 | 65.44717011 | 0.451 | 200 lbs/v 0.02 in/v |
| STS 11 | 3.7735 | 1.9135 | 1041.92 | 28.4211868 | 36.65997509 | 0.253 | 91.90981697 | 0.634 | 100 lbs/v 0.02 in/v |

*All results that differed by more 20% were discarded, ones that differed by 20% are shown in yellow.

| Mean of Maximum Load (lbf) | Mean of Splitting Tensile Strength (psi) | Standard deviation of Splitting Tensile Strength (psi) | Mean of Compressive Strength (psi) | Standard deviation of Compressive Strength (psi) |
|---|---|---|---|---|
| 943.10 | 75.86 | 11.32 | 36.26 | 4.49 |




- **Capillary water absorption** *2.7. Part I Laboratory Testing Procedure* (GCI 2011, 35):

Calculations used to calculate the capillary water absorption:

$$\Delta M_t = M_t - M_0$$

$$m = \frac{\Delta M_t}{\pi \times \left(\frac{d^2}{2}\right)} \times 10^3$$

l(mm): Length of the specimen

d(mm): Diameter of the specimen

$M_0$(g): Dry weight of the specimen at time t

t(s): Time

$M_0$ (g): Weight of the specimen at time t

$\Delta M_t$ (g): Weight of absorbed water after rime t

$M(kg \times m^{-2})$: Weight of absorbed water per unit area

| **Grout Name** | TUMA Soil Grout |
|---|---|
| **Grout Proportions** | 2.5: 1 (solid to water) |
| **Operator** | Nicole Declet |
| **Date** | 21-Mar-17 |

| Time *t*(s) | 3:20:00 PM | 3:20:30 PM | 3:22:00 PM | 3:25:00 PM | 3:30:00 PM | 3:35:00 PM | 3:50:00 PM | 4:20:00 PM | 5:20:00 PM | 6:20:00 PM | 7:20:00 PM | 8:20:00 PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Interval (s) | 30 | 1 | 2 | 5 | 10 | 15 | 30 | 60 | 120 | 180 | 240 | 300 |
| **M*t*** | 216.34 | 215.52 | 214.59 | 213.18 | 210.98 | 209.07 | 201.81 | 184.36 | 160.84 | 142.14 | 118.45 | 91.76 |
| **ΔMt** | -0.12 | -0.94 | -1.87 | -3.28 | -5.48 | -7.39 | -14.65 | -32.1 | -55.62 | -74.32 | -98.01 | -124.7 |
| **m (kg*m −2)** | -6.84E-05 | -5.36E-04 | -1.07E-03 | -1.87E-03 | -3.12E-03 | -4.21E-03 | -8.35E-03 | -1.83E-02 | -3.17E-02 | -4.24E-02 | -5.59E-02 | -7.11E-02 |

Specimen 1:

| Specimen no. | Length (in) | Diameter (in) | Dry weight of the specimen (t=0) | Dry weight II | Mo Dry weight III | Container (Wg) | Container+ Mesh+ Stoppers | Container +Mesh+Stopper+Water | After experiment |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.25 | 1.495 | 241.93 | 216.3 | 216.46 | 1047.56 | 1167.77 | 2049.13 | 2248.36 |
| 2 | 4.25 | 1.476 | 250.64 | 218.3 | 218.27 | 966.1 | 1087.26 | 1957.94 | 2160.4 |
| 3 | 4.125 | 1.479 | 237.48 | 206.09 | 206.04 | 963.94 | 1084.12 | 1877.05 | 2066.05 |

Specimen 2:

| Time *t*(s) | 3:20:00 PM | 3:20:30 PM | 3:22:00 PM | 3:25:00 PM | 3:30:00 PM | 3:35:00 PM | 3:50:00 PM | 4:20:00 PM | 5:20:00 PM | 6:20:00 PM | 7:20:00 PM | 8:20:00 PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Interval (s) | 30 | 1 | 2 | 5 | 10 | 15 | 30 | 60 | 120 | 180 | 240 | 300 |
| **M*t*** | 218.23 | 217.32 | 216.35 | 215 | 212.98 | 211.08 | 206.4 | 192.33 | 170.82 | 146.57 | 129.6 | 111.32 |
| **ΔMt** | -0.04 | -0.95 | -1.92 | -3.27 | -5.29 | -7.19 | -11.87 | -25.94 | -47.45 | -71.7 | -88.67 | -106.95 |
| **m (kg*m −2)** | -2.34E-05 | -5.55E-04 | -1.12E-03 | -1.91E-03 | -3.09E-03 | -4.20E-03 | -6.94E-03 | -1.52E-02 | -2.77E-02 | -4.19E-02 | -5.18E-02 | -6.25E-02 |

Specimen 3:

| Time *t*(s) | 3:20:00 PM | 3:20:30 PM | 3:22:00 PM | 3:25:00 PM | 3:30:00 PM | 3:35:00 PM | 3:50:00 PM | 4:20:00 PM | 5:20:00 PM | 6:20:00 PM | 7:20:00 PM | 8:20:00 PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Interval (s) | 30 | 1 | 2 | 5 | 10 | 15 | 30 | 60 | 120 | 180 | 240 | 300 |
| **M*t*** | 206.41 | 205.56 | 204.42 | 203.1 | 200.9 | 198.86 | 193.13 | 183.27 | 158.59 | 133.57 | 120.82 | 106.21 |
| **ΔMt** | 0.37 | -0.48 | -1.62 | -2.94 | -5.14 | -7.18 | -12.91 | -22.77 | -47.45 | -72.47 | -85.22 | -99.83 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **m (kg*m −2)** | 2.15E-04 | -2.80E-04 | -9.43E-04 | -1.71E-03 | -2.99E-03 | -4.18E-03 | -7.52E-03 | -1.33E-02 | -2.76E-02 | -4.22E-02 | -4.96E-02 | -5.81E-02 |

- **Water retention** *3.2. Part I Laboratory Testing Procedure* (GCI 2011, 51):

The water retention value was calculated using the following:

$\mathrm{M_W}$ (g): Weight of the water used during grout mixing

$\mathrm{M_{dg}}$ (g): Total weight of dry grout ingredients used during grout mixing

$\mathrm{M_1}$ (g): Weight of perforated dish and wet filter paper

$\mathrm{M_2}$ (g): Weight of perforated dish and wet filter paper with grout

$\mathrm{M_3}$ (g): Weight of perforated dish and wet filter paper with grout after suction

$\mathrm{M_g}$ (g): Weight of grout in the perforated dish

$$\mathrm{M_G} = \mathrm{M_2} - \mathrm{M_1}$$

ω: Water to grout weight ratio

$$\omega = \frac{\mathrm{M_W}}{\mathrm{M_W} + \mathrm{M_{dg}}}$$

$\mathrm{W_1}$ (g): Water content of the grout before suction

$\mathrm{W_2}$ (g): Weight of water extracted by suction

$$\mathrm{W_1} = \omega \times \mathrm{M_G}$$

WRV (%): Water retention value

$$\mathrm{WRV} = \left(1 - \frac{\mathrm{W_2}}{\mathrm{W_1}}\right) \times 100$$

| | | | |
|---|---|---|---|
| **Grout Name** | TUMA Soil Grout | **Temperature (C°)** | 21 |
| **Grout Proportions** | 2.5: 1 (solid to water) | **RH (%)** | 30 |
| | | **Date** | 4/11/2017 |
| **Operator** | Nicole Declet | **Room** | ACL Laboratory |

| Specimen # | Mw (g) | Mdg (g) | ω |
|---|---|---|---|
| 1 | 124.33 | 415.17 | 0.23 |
| 2 | 124.29 | 414.55 | 0.23 |

| Specimen # | M1 (g) | M2 (g) | Mg (g) | W1 (g) | M3 (g) | W2 (g) | WRV % |
|---|---|---|---|---|---|---|---|
| 1 | 271.2 | 672.48 | 401.28 | 92.48 | 668.08 | -4.4 | 104.76 |
| 2 | 270.21 | 658.45 | 388.24 | 89.58 | 654.05 | -4.4 | 104.91 |

**PRACTICE TESTS FOR COMPARISON: #1**

| | | | |
|---|---|---|---|
| **Grout Name** | NHL 3.5: Yellow Sand: Water | **Temperature (C°)** | 21 |
| **Grout Proportions** | 3.2: 1 (solid to water) | **RH (%)** | 30 |
| | | **Date** | 4/11/2017 |

| Specimen # | Mw (g) | Mdg (g) | ω |
|---|---|---|---|
| 1 | 139.8 | 445.23 | 0.24 |

| Specimen # | M1 (g) | M2 (g) | Mg (g) | W1 (g) | M3 (g) | W2 (g) | WRV % |
|---|---|---|---|---|---|---|---|
| 1 | 272.64 | 651.74 | 379.1 | 90.98 | 611.84 | -39.9 | 143.86 |

**PRACTICE TESTS FOR COMPARISON: #2**

| | | | |
|---|---|---|---|
| **Grout Name** | Soil B (ASTM #8 sieve): Water | **Temperature (C°)** | 21 |
| **Grout Proportions** | 2.5: 1 (solid to water) | **RH (%)** | 30 |
| | | **Date** | 4/11/2017 |

| Specimen # | Mw (g) | Mdg (g) | ω |
|---|---|---|---|
| 1 | 81.26 | 256.26 | 0.24 |

| Specimen # | M1 (g) | M2 (g) | Mg (g) | W1 (g) | M3 (g) | W2 (g) | WRV % |
|---|---|---|---|---|---|---|---|
| 1 | 273.31 | 528.5 | 255.19 | 61.25 | 511.11 | -17.39 | 128.39 |

PRACTICE TESTS FOR COMPARISON: #3

| Grout Name | Soil B (ASTM #8 sieve): HMP | Temperature (C°) | 21 |
|---|---|---|---|
| Grout Proportions | 2.5: 1 (solid to liquid) | RH (%) | 30 |
| | | Date | 4/11/2017 |

| Specimen # | Mw (g) | Mdg (g) | ω |
|---|---|---|---|
| 1 | 124.53 | 343.51 | 0.27 |

| Specimen # | M1 (g) | M2 (g) | Mg (g) | W1 (g) | M3 (g) | W2 (g) | WRV % |
|---|---|---|---|---|---|---|---|
| 1 | 273.27 | 677.06 | 403.79 | 109.02 | 671.94 | -5.12 | 104.70 |

- **Permeability (WPT)**

The water vapor transmission rate was calculated using the following formula:

$$\mathrm{WVT} = \frac{\mathrm{G}}{\mathrm{tA}}$$

Where G= weight change (grams)

t= time (hours)

G/t= slope of the straight line (g/h)

A= test area ($\mathrm{cm}^2$)

WVT= rate of water vapor transmission (g/h/$\mathrm{cm}^2$)

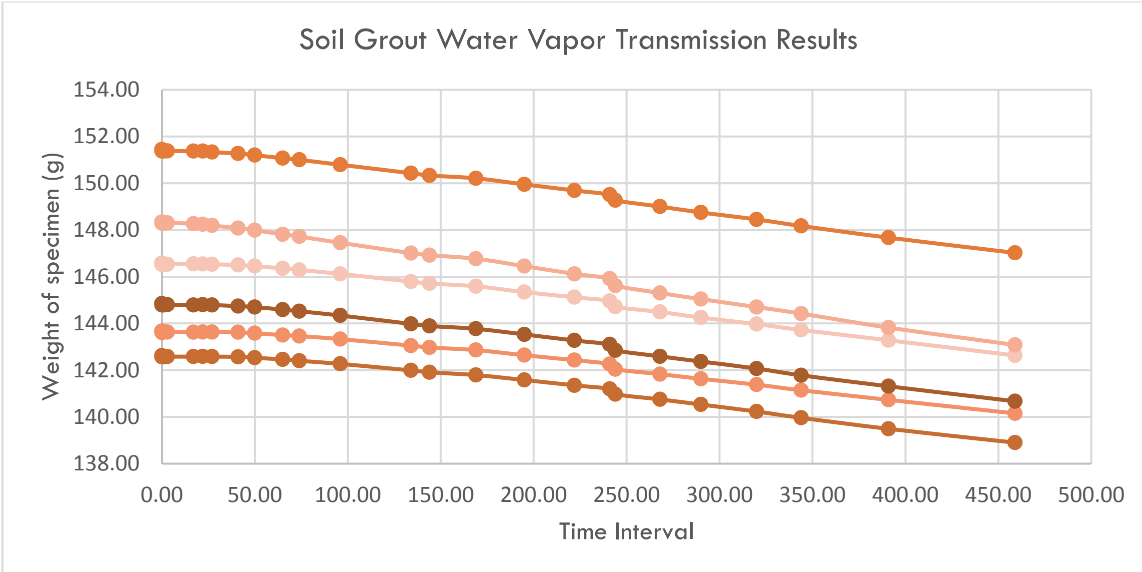
| DATE | TIME | INTERVAL | DISK 1 Mn (g) | DISK 2 Mn (g) | DISK 3 Mn (g) | DISK 4 Mn (g) | DISK 5 Mn (g) | DISK 6 Mn (g) |
|---|---|---|---|---|---|---|---|---|
| **3/14/2017** | 8:00:00 PM | 0.00 | 146.58 | 148.34 | 143.67 | 151.44 | 142.62 | 144.85 |
| **3/14/2017** | 8:05:00 PM | 0.08 | 146.52 | 148.28 | 143.61 | 151.37 | 142.57 | 144.79 |
| **3/14/2017** | 8:15:00 PM | 0.25 | 146.54 | 148.29 | 143.63 | 151.39 | 142.58 | 144.80 |
| **3/14/2017** | 8:30:00 PM | 0.50 | 146.53 | 148.3 | 143.62 | 151.38 | 142.57 | 144.80 |
| **3/14/2017** | 9:00:00 PM | 1.00 | 146.52 | 148.28 | 143.63 | 151.37 | 142.57 | 144.79 |
| **3/14/2017** | 11:00:00 PM | 3.00 | 146.53 | 148.3 | 143.63 | 151.38 | 142.58 | 144.8 |
| **3/15/2017** | 1:00:00 PM | 17.00 | 146.55 | 148.27 | 143.62 | 151.37 | 142.58 | 144.79 |
| **3/15/2017** | 6:00:00 PM | 22.00 | 146.54 | 148.24 | 143.63 | 151.37 | 142.59 | 144.8 |
| **3/15/2017** | 11:00:00 PM | 27.00 | 146.53 | 148.19 | 143.63 | 151.33 | 142.58 | 144.79 |
| **3/16/2017** | 1:00:00 PM | 41.00 | 146.5 | 148.08 | 143.62 | 151.27 | 142.57 | 144.74 |
| **3/16/2017** | 10:00:00 PM | 50.00 | 146.45 | 147.99 | 143.58 | 151.2 | 142.53 | 144.7 |
| **3/17/2017** | 1:00:00 PM | 65.00 | 146.36 | 147.81 | 143.5 | 151.07 | 142.46 | 144.59 |
| **3/17/2017** | 10:00:00 PM | 74.00 | 146.29 | 147.72 | 143.46 | 151 | 142.4 | 144.52 |
| **3/18/2017** | 8:00:00 PM | 96.00 | 146.12 | 147.45 | 143.33 | 150.79 | 142.27 | 144.34 |
| **3/20/2017** | 1:00:00 PM | 134.00 | 145.79 | 147.01 | 143.05 | 150.43 | 141.99 | 143.98 |
| **3/20/2017** | 11:00:00 PM | 144.00 | 145.71 | 146.92 | 142.97 | 150.33 | 141.91 | 143.89 |
| **3/21/2017** | 12:00:00 PM | 169.00 | 145.59 | 146.77 | 142.86 | 150.21 | 141.79 | 143.77 |
| **3/22/2017** | 2:00:00 PM | 195.00 | 145.34 | 146.45 | 142.64 | 149.95 | 141.58 | 143.53 |
| **3/23/2017** | 5:00:00 PM | 222.00 | 145.12 | 146.12 | 142.43 | 149.69 | 141.35 | 143.27 |
| **3/24/2017** | 12:00:00 PM | 241.00 | 144.96 | 145.92 | 142.26 | 149.51 | 141.2 | 143.1 |
| **3/25/2017** | 3:00:00 PM | 244.00 | 144.71 | 145.62 | 142.04 | 149.27 | 140.97 | 142.85 |
| **3/26/2017** | 3:00:00 PM | 268.00 | 144.49 | 145.3 | 141.83 | 149 | 140.75 | 142.59 |
| **3/27/2017** | 1:00:00 PM | 290.00 | 144.25 | 145.04 | 141.63 | 148.75 | 140.53 | 142.37 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **3/28/2017** | 7:00:00 PM | 320.00 | 143.97 | 144.7 | 141.38 | 148.45 | 140.23 | 142.07 |
| **3/29/2017** | 7:00:00 PM | 344.00 | 143.72 | 144.42 | 141.14 | 148.17 | 139.96 | 141.78 |
| **3/31/2017** | 6:00:00 PM | 391.00 | 143.28 | 143.82 | 140.73 | 147.67 | 139.49 | 141.31 |
| **4/3/2017** | 2:00:00 PM | 459.00 | 142.63 | 143.08 | 140.15 | 147.02 | 138.9 | 140.67 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Change in weight (g) | 0.74 | 0.92 | 0.66 | 0.82 | 0.74 | 0.78 |
| Diameter (d) in | 1.90 | 1.92 | 1.90 | 1.90 | 1.90 | 1.89 |
| Diameter (d) mm | 48.26 | 48.77 | 48.26 | 48.26 | 48.26 | 48.01 |
| Diameter (d) m | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Diameter (d) cm | 4.83 | 4.88 | 4.83 | 4.83 | 4.83 | 4.80 |
| Area (a) in cm | 18.31 | 18.69 | 18.31 | 18.31 | 18.31 | 18.09 |
| Time (interval) hours | 76.00 | 76.00 | 76.00 | 76.00 | 76.00 | 76.00 |
| g/t | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| g/t/a | **5.32E-04** | **6.48E-04** | **4.74E-04** | **5.89E-04** | **5.32E-04** | **5.67E-04** |
| units | **g/(h/cm^2)** | **g/(h/cm^2)** | **g/(h/cm^2)** | **g/(h/cm^2)** | **g/(h/cm^2)** | **g/(h/cm^2)** |

| *Same result in different units (to compare with outside reports)* | | | | | | |
|---|---|---|---|---|---|---|
| Area (a) in m | 0.001828287 | 0.00186713 | 0.001828287 | 0.001828287 | 0.001828287 | 0.001809394 |
| g/t/a | **5.33** | **6.48** | **4.75** | **5.90** | **5.33** | **5.67** |
| units | **g(h/m^2)** | **g(h/m^2)** | **g(h/m^2)** | **g(h/m^2)** | **g(h/m^2)** | **g(h/m^2)** |

| | | |
|---|---|---|
| Average | 5.57E-04 | g/(h/cm^2) |
| Average | 5.58 | g(h/m^2) |




- **Shear Bond Strength (mock-up)** *3.5. Part I Laboratory Testing Procedure* (GCI 2011, 62):
  The shear bond strength of the assemblies was calculated by using the following formula:

$$f_{sb} = \frac{F}{w \times l}$$

Where:

w(mm): Width of failed grout area

l(mm): Length of failed grout area

F(N): Breaking Load

$f_{sb}(N \times mm^{-2})$: Shear Bond Strength

| **Grout Name** | TUMA Soil Grout | **Age of specimen (days)** | 21 days |
|---|---|---|---|
| **Grout Proportions** | 2.5: 1 (solid to water) | | |
| **Operator** | Dr. Alex Radin | **Date** | April 6, 2017. |

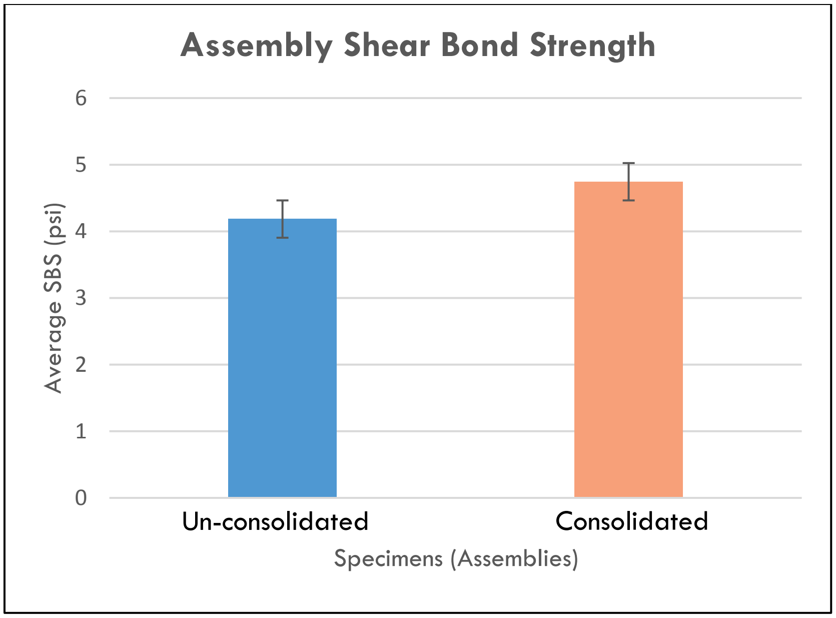
| **Unconsolidated** | Gap width | Width of failed grout area w (in) | Length of failed grout area l (in) | Breaking load F (lb) | Shear Bond Strength (lb*in–2) |
|---|---|---|---|---|---|
| (-) B1 | 1/2" | 2.8125 | 3.6805 | 38.01 | 3.67196486 |
| (-) B2 | 1/2" | 2.6585 | 3.743 | 27.67 | 2.780690591 |

| | | | | | |
|---|---|---|---|---|---|
| (-) B3 | 1/4" | 2.999 | 3.753 | 66.59 | 5.916351725 |
| (-) B4 | 1/4" | 2.611 | 3.655 | 29.3 | 3.070247364 |
| (-) B5 | 1/4" | 2.793 | 3.783 | 53.27 | 5.041681656 |
| (-) B6 | 1/4" | 2.8535 | 3.7705 | 62.82 | 5.838766533 |
| (-) B8 | 1/2" | 2.731 | 3.599 | 38.4 | 3.90685846 |
| (-) B9 | 1/4" | 2.558 | 3.6295 | 57.8 | 6.225589737 |
| (-) B10 | 1/2" | 2.7235 | 3.695 | 12.12 | 1.204372408 |

| **Consolidated** | Gap width | Width of failed grout area w (in) | Length of failed grout area l (in) | Breaking load F (lb) | Shear Bond Strength (lb*in–2) |
|---|---|---|---|---|---|
| A1 | 1/4" | 2.907 | 3.65 | 56.73 | 5.346565447 |
| A4 | 1/4" | 2.747 | 3.657 | 30.21 | 3.007233187 |
| A6 | 1/4" | 2.8465 | 3.708 | 49.84 | 4.722012366 |
| A7 | 1/4" | 2.7495 | 3.7055 | 57.36 | 5.630002673 |
| A8 | 1/2" | 2.889 | 3.78 | 22.19 | 2.031973129 |
| A9 | 1/4" | 2.756 | 3.6695 | 28.57 | 2.825036967 |
| A10 | 1/4" | 2.877 | 3.726 | 161.19 | 15.0367986 |
| A11 | 1/2" | 2.738 | 3.7325 | 24.44 | 2.391486543 |
| B11 | 1/2" | 2.725 | 3.6025 | 41.25 | 4.201974928 |
| B14 | 1/2" | 2.711 | 3.779 | 23.05 | 2.249906758 |

| | Width of grout area w (in) | Length of grout area l (in) | Breaking load F (lb) | Shear Bond Strength (lb*in–2) |
|---|---|---|---|---|
| Unconsolidated | 2.78 | 3.69 | 43.23 | 4.21 |
| Consolidated | 2.81 | 3.67 | 51.30 | 4.98 |

| | Mean of Maximum Load (lbf) | Mean of Shear Bond Strength(psi) | Standard deviation of SBS (psi) | Variance | T-Test P value | T-Test 2-Tail P |
|---|---|---|---|---|---|---|
| Non-consolidated | 43.2266667 | 4.21 | 1.7 | 3.85 | 0.015 | 0.683 |
| Consolidated | 51.295 | 4.98 | 3.85 | 14.8 | | |


Assembly Shear Bond Strength
Average SBS (psi)
6
5
4
3
2
1
0
Un-consolidated
Consolidated
Specimens (Assemblies)

# Index