Assessment of the Grout Used for the Structural Stabilization of the Early Phrygian Citadel Gate at Gordion, Turkey

Kelly H. Wong
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Kelly Hai Wong

A THESIS

In

Historic Preservation

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

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IN HISTORIC PRESERVATION

2006

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In Memory of Steven

My little scientist
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1.0 INTRODUCTION

Only a few sites in the world offer a glimpse of the early civilizations during the Late Bronze and Iron Ages. Gordion is one of the key sites in central Anatolia which premiers a royal center from the Iron Age Phrygian period and features a monumental 9th century B.C. Early Phrygian Gate structure along with the remains of a once impressive Terrace Building complex and stately Megaron buildings. Although the site today is more prominently associated with the reign of King Midas, who led the Phrygian Empire to its zenith at the end of the 9th century, its continuous occupation for over 3,000 years in addition to the ongoing archaeological excavations and research since the 1950s has made Gordion a unique and rich repository for scholars, visitors, and students alike interested not only in the history of ancient Anatolia, the rise and fall of several great empires, but also the conservation issues regarding the protection and maintenance of cultural fabric within a world renowned historical center.

Although Gordion is an archaeological site of unparalleled significance, the existing architectural features on site have been exposed to natural weathering for over 50 years and are currently in a poor state of deterioration. The monumental Citadel Gate is particularly vulnerable to effects of periodic seismic activity in the region. Gordion is located approximately 100 km southwest of Ankara, in west-central Turkey. Situated south of the North Anatolian Fault, one of the world's longest strike-slip faults, Gordion also experienced the effects of the 7.4 magnitude Izmit earthquake on August 17, 1999.
As a result of this seismic activity, the structural integrity of the Citadel Gate was seriously distressed and caused great concern for the future stability of the structure.

1.1 Research Aims

In 2002, a formal grout injection program for the stabilization of the Citadel Gate structure was established. The grout specified for consolidating the unreinforced masonry walls was a hydraulic lime-based mixture using local sand and crushed brick. The research presented in this thesis assesses the performance characteristics of three grout formulations based on the one previously specified to structurally consolidate the rubble core-veneer masonry system at the Early Phrygian Citadel Gate. This includes the assessment of the physical-chemical and mechanical properties of the grouts, as well as their ability to reintegrate discontinuities (e.g. detachment and cracking) by filling voids, and anchoring the veneer against stress caused by earthquake movement. Moreover, this study discusses the parameters for evaluating the properties of injection grouting applied specifically to historic unreinforced masonry structures, as well as the alternatives to further strengthen this type of masonry construction system.

1.2 Assumptions

Since access to the site was not an option (work permits for archaeological sites in Turkey are based on specific excavation season dates which did not fall within the time span of this research), a number of assumptions were made during the research program.
The first assumption is that there are voids in the cross-section of the Early Phrygian Citadel Gateway wall assembly and that these voids are continuous and can be grouted for the consolidation of the wall system. The second assumption is that use of grouting is the most viable treatment for stabilizing the Citadel Gate with the lowest impact on the site. And the third assumption is that earthquake activity will occur at this site in the future.

1.3 Research Contents

The contents of this thesis research are:

- Site overview including the historical background and evolution of the site, excavation history and past conservation treatments;

- Review of the current literature on grouts and grouting for art and architectural conservation, as well as civil engineering;

- Results and discussion of a laboratory testing program testing the physical-chemical and mechanical properties of three grout formulations;

- Alternative repair methods for stabilizing the Citadel Gate structure; and

- Recommendations for future conservation of the Citadel Gate.
2.0 SITE OVERVIEW

2.1 Site Background

Gordion was the ancient capital of Phrygia, lying on the right bank of the Sakarya (ancient Sangarios) River approximately 100 kilometers (60 miles) southwest of Ankara, the current capital of Turkey. The site not only offered a central location in west-central Anatolia for communication across the region for an active trade center but its fertile valley and natural springs were desirable for cultivating wheat and barely as well as providing pastures for herding.

Distinct in its large settlement mound, “Yassihöyük,” which gives its name to the modern village, Gordion is also unique in its landscape of surrounding tumuli, massive earthen burial mounds (Fig. 2.1). The site sat unnoticed since its last occupation during Seljuk times between 11th and 13th centuries until it was discovered by German Classicist Alfred Körte in November 1893. During the early 20th century when competition to excavate
the most prominent archaeological sites existed among American universities, the University of Pennsylvania began excavations at Gordion in 1950 under the direction of archaeologist and scholar Rodney S. Young (Fig. 2.2). Since then, the campaigns have revealed an extensive history of ancient settlement of over 3,000 years and currently premiers a royal center in Central Anatolia during the Iron Age that does not exist anywhere else.

Today, the site is more prominently known for its association with King Midas, his leadership during the height of the Early Phrygian Kingdom as well as the location of his tomb. However, new chronologies using dendrochronology\(^1\) and radio-carbon dating have been established for the wooden tomb as well as for the Destruction Level.\(^2\) This section of the Site Overview will begin with a description of the site

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\(^1\) Dendrochronology is the scientific dating system that uses the distinctive pattern of yearly tree-rings.

\(^2\) Dr. Peter Kunihom, the current Director of the Malcom and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University and once a graduate student working under Rodney Young conducted the dendrochronology analysis of the juniper logs in the wooden tomb uncovered in 1957. Kunihom’s previous date for cutting the juniper logs was 718 BC, a date compatible with the building of a tomb for King Midas whose death was believed to be around the end of the late 8\(^{th}\) century BC. The new dendrochronology study reveals a shift in the date of the cutting to 740 BC which leads to the reevaluation of the occupant of the tomb. Additionally, radio-carbon dating of seeds found on the floor of Terrace Building 2A within the Destruction Level produced calibrated dates of 830-800 BC, suggesting an earlier construction date than previously known (originally dated 750 BC) (Lisa Kealhofer, ed. *The Archaeology of Midas and the Phrygians*. Philadelphia: The University Museum, University of Pennsylvania, 2005. 31). This data has led to the reconsideration of previously identified dates recorded in past records, specifically during the Young campaigns and has been incorporated into this chronology.
evolution including the Citadel Gate complex, followed by the excavation history, and conclude with the conservation history.

2.1.1 Site Evolution

Gordion was the capital of the Phrygian Kingdom in the 9th and 8th centuries BC and at the height of its prosperity near the end of the 8th and beginning of the 7th centuries under the leadership of King Midas. Archaeological evidence has shown that the site was inhabited as early as 2000 BC during the Early Bronze Age and afterwards may have been a significant center for the Hittite Empire. After the collapse of the Hittite polity in ca. 1200 BC, an Indo-European people called the Phrygians settled in Central Anatolia and established Gordion as their capital in the 9th c. BC. An Iron Age (1100-300 BC) civilization, the Phrygians occupied the site through two known periods, the Early Phrygian (950-800 BC) and Middle Phrygian (c. 800-540 BC). According to Mary Voigt, the current Director of Excavations and Survey for the Gordion Excavation Project, the Early Phrygian period can be seen in three phases during the construction of the Old Citadel: Initial Early Phrygian (c. 950-900 BC), Early Phrygian (c. 900-800 BC), and Early Phrygian Destruction (800 BC). After a catastrophic fire around 800 BC, the Old Citadel was covered over and the site remained fallow until it was cleared to make

room for the New Citadel in the Middle Phrygian period (c. 800-540 BC). The New Citadel is constructed almost exactly on top of the Old Citadel in a similar footprint which remained occupied through the end of the Phrygian Empire. Although it was originally believed that the Early Phrygian period was the most prominent at Gordion, the new dates reveal that the Middle Phrygian as the period when the Phrygians are at the height of their prosperity under the leadership of King Midas. After the death of Midas, the Middle Phrygian kingdom falls under the Lydian empire until their defeat by the Achaemenids (a Persian tribe) in ca. 550 BC, at which time Gordion becomes their outpost for the next 200 years. In 334 BC, Alexander the Great establishes the site as winter headquarters during his first campaign against the Persians. After the Persians are defeated, Gordion becomes less significant until the Galatians settle at the end of 200 BC. During the Hellenistic occupation, the various levels of the Phrygian site were filled to make one single citadel mound which would later be settled by the Romans and used through the late Medieval period. See Table 2.1 for the current historical and stratigraphic sequence at Gordion provided by Voigt.

---

7 Ibid.
Table 2.1. Historical and Stratigraphic Sequence at Gordion

<table>
<thead>
<tr>
<th>Phrygian Citadels</th>
<th>Period Names</th>
<th>Approximate Absolute Dates</th>
<th>YHSS Phases</th>
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<tr>
<td></td>
<td>Middle Bronze Age</td>
<td>c. 2000-1500 BC</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Late Bronze Age</td>
<td>c. 1500-12\textsuperscript{th} century BC</td>
<td>8-9</td>
</tr>
<tr>
<td></td>
<td>Early Iron Age</td>
<td>c. 12\textsuperscript{th} century BC – c. 950 BC</td>
<td>7</td>
</tr>
<tr>
<td>Old Citadel</td>
<td>Initial Early Phrygian</td>
<td>c. 950-900 BC</td>
<td>6B</td>
</tr>
<tr>
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<td>Early Phrygian</td>
<td>c. 900-800 BC</td>
<td>6A</td>
</tr>
<tr>
<td></td>
<td>Early Phrygian Destruction</td>
<td>800 BC</td>
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<td>Medieval</td>
<td>13\textsuperscript{th}-14\textsuperscript{th} century AD</td>
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</tr>
</tbody>
</table>

2.1.2 Citadel Gate

The Citadel Gate was originally constructed in the mid 9\textsuperscript{th} century BC during the Early Phrygian period (c. 900-800 BC) as part of an expansion of the Old Citadel area. The earlier citadel fortification walls were torn down and replaced with new extended walls which incorporated the Polychrome House originally attached to the citadel walls, to be included in the inner town. Megaron 9 was built over the location of the previous entrance, the Early Phrygian Building located at the northeastern quadrant of the site. During this period, the cobbled courtyard between the heavy enclosure wall and the Gate complex was covered with filling, leveled, and recovered with slab stone paving. Additionally, two small storage rooms were added to the rear of Megaron 2 to accommodate the larger citadel (Fig. 2.3).
The Citadel Gate is known to have served as the city’s entrance for only a short period spanning between ca. 850 to 875 century BC. The Gate complex in c. 875 BC was closed off to the rest of the Citadel and the Terrace Gateway was constructed as the new entrance to the upper level southwestern Terrace Complex. The Gate complex is thus used as storage after 875 BC, later covered after the great fire in late 800 BC, and eventually reincorporated into the New Citadel Gate built during the Middle Phrygian period.
In ca. 850 BC, the Citadel Gate served as the formal entrance into the city and was constructed of buff-colored massive ashlar limestone laid in rough courses with earthen mortar and facing a rubble core. The exterior walls battered outwards at approximately five centimeters per one meter in height for stability and a brown earthen plaster finish was applied to protect and possibly decorate with lime wash.

The monumental Gate complex stood at a height of almost 10 meters and consisted of four separate elements: the central ramp, the gate house (previously the Polychrome House), the North Court building, and the South Court building. The cobbled paved central ramp, with an almost precise east-west orientation penetrated the newly constructed fortification wall and shared an open cross-wall at the top of its slope with the gate house at its inner (western) end. The central ramp led up to the gate house, which is in actuality the Polychrome House that was previously constructed as part of the earlier citadel. It is known as the Polychrome House because of the various colored stones used for its construction and its doorway at the east wall served as the actual gate of the Phrygian Gate building. The northwest-southeast orientation of the Polychrome House made an obtuse angle at the cross-wall where the east-west running central ramp met. This cross-wall belonged structurally to the enclosed Polychrome House. The

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11 Ibid. 234.
wall opposite the cross-wall (west wall) was open at the center to allow passage through
the gate and the Polychrome house before entering the citadel.

The North and South Court buildings flanked the ramp at varying angles. While their
exterior walls were typically battered for support, their interior court walls were built
vertical. The North Court building had the same orientation as the central ramp where
the southern wall abutted the northeastern corner of the Polychrome House. Its wall
thicknesses were irregular and more slender than those of the South Court. Its interior
court measured 12.5 meters wide and probably had a roof. The floor construction was
rather complex and consisted of several layers, starting from the bottom: the first original

Figure 2.4. A 3-D rendering of the Old Citadel Gate complex during the Early
Phrygian period (Banu 2004).
floor, a lighter earthen layer of (40 cm), second floor of hard earth, and a darker layer.
Partition walls sat on top of sun-dried brick which rested on large wooden floor beams laid above small stone rubble that was covered by a smooth layer of clay.12

The South Court building, on the other hand, was not parallel to the ramp and met the southeastern corner of the Polychrome House and followed its northwest-southeast orientation. Its walls were approximately four meters thick, except at the northeast where it met the central ramp. Like the west wall of the Polychrome House, the west wall of the South Court building opened at the center to the citadel.13 Neither court buildings were accessible from the central ramp and could be entered only through their front (western) façades.

By the third quarter of the 9th century BC, as part of the Terrace Project, a light mud brick enclosure wall was constructed between Megarons 1 and 9 which closed off the area within the gate complex from the rest of the citadel. The gate complex is no longer a main artery and serves as a training area for soldiers or storage facility; the North Court building was used for storage of large pithoi at one time.14 The Terrace project also changed the topography and the aesthetics of the site considerably with the construction

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of the southwestern terrace complex which included the Terrace Building, CC Building, and a new Terrace Gateway constructed 2 meters above the Citadel Gate level. The Terrace level represented the city’s center of production in grain preparation and textile.

At the end of the 9th century BC, the final construction phase of the Old Citadel before the great fire, the Citadel Gate was dismantled during another terracing operation undertaken to install a new drainage system for the enclosed courtyard. The roof and walls of the Polychrome House appear to be absent at the time of the fire. This may have occurred in order to make room for the construction of the new drainage system (Fig. 2.5).

![Figure 2.5. Early Phrygian Period Destruction Level Plan after fire in 800 BC (Alblinger 2002).](image-url)
The catastrophic fire in late 800 BC destroyed most of the Old Citadel. The Phrygians buried these ruins under a layer (3-5 meters) of clay soil\textsuperscript{15} which in turn significantly contributed to their remarkable state of preservation. This layer is known as the “Destruction Level” and also the stratum associated with the majority of the excavated buildings that are visible today.

After the fire, the site laid fallow until a major rebuilding stage was initiated to construct a New Citadel during the Middle Phrygian period (c. 800-540 BC) which used a similar footprint as the Old Citadel.\textsuperscript{16} Both citadel fortifications represent common construction traditions in northwestern Anatolia.\textsuperscript{17} The New Citadel was believed to have been constructed by the Phrygians, under the Lydian Empire which purged the Kimmerians from Anatolia. Young called the Middle Phrygian citadel the “Persian Level”; the New Citadel gate complex was thus called the “Persian Gate” (Fig. 2). Part of the New Citadel gate complex was built directly upon the remains of the earlier Old Citadel gate structure but with more massive, more finely finished limestone that was interspersed with rosy hued chinking stones.\textsuperscript{18}

\textsuperscript{18} Rogers. 1989. 47.
The Lydians remained at Gordion until the mid 6th century when they were conquered by the Persians, during the Achaemenid period. The Persians used Gordion as an outpost for the next 200 years.\textsuperscript{19} In 334 BC, Alexander the Great established his winter headquarters during his first campaign against the Persians.\textsuperscript{20} After the defeat of the Persians, the site


became less significant. Around 300-100 BC, the Galatians settled at Gordion until they fled from the Roman army. The double mounds found during both the occupation of the Old and New Citadels was finally flattened at the end of the 4th century BC and the eastern valley was filled to create one single mound before the first Hellenistic settlement. In the 1st to 4th centuries AD, the western edge of Gordion became a minor settlement of the Roman Empire. The last known period of occupation at the site was during the late medieval period between the 11th and 13th centuries by the Seljuk Turks.

2.2 Excavation History

German Classicist Alfred Körte first discovered Gordion in 1893 and returned seven years later.

Figure 2.7. Drilling Rig Team in 1955 (Gordion Archives 1955).

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23 Professor Dr. Kenneth Sams and Mr. İlhan Temizsoy. Gordion Museum. Gordion: Republic of Turkey, Ministry of Culture, General Directorate of Monuments and Museums. 2000. 7.
with his brother Gustav to conduct a single, three-month long season of excavation in 1900.\footnote{Lisa Kealhofer, ed. \textit{The Archaeology of Midas and the Phrygians}. Philadelphia: The University Museum, University of Pennsylvania, 2005. 10.} Their time was split between digging trenches at the southwestern edge of the Citadel mound and opening five burial mounds, today known as Körte I-V. Though the excavations at the mound reached levels which dated back to the 6\textsuperscript{th} century BC, the findings in the burial mounds ranged further, between 8\textsuperscript{th} and 6\textsuperscript{th} centuries BC with rich furnishings dated from the peak of the old Phrygian period when King Midas ruled in the 8\textsuperscript{th} century BC.\footnote{Ibid.}

Under the auspices of the University of Pennsylvania, Rodney S. Young was granted permission by the Turkish government to begin excavations at Gordion in the spring of 1950. With the primary goal of learning more about the little-known Phrygian civilization, Young conducted over 17 excavations through 1973 until his death in 1974.\footnote{Ibid. 12.}

The main settlement mound (Citadel mound) measures approximately 500 m east-west and 400 m north-south. Its highest area is found along the western half of the mound which rises to nearly 16.5 m above datum (river surface in 1950) which was found to be settled during the Roman and later Medieval periods. Its lower eastern portion at a
maximum level of 13 m high that was occupied by an earlier Phrygian people. Over the entire mound was a Hellenistic settlement. The discovery of the different occupation levels prompted Young to shift his focus to the eastern half of the mound, where he began excavations starting his second season. Excavations in the 1950s gradually revealed two major levels of monumental architecture within the Phrygian period, the Old Citadel and the New Citadel separated by the clay fill after the catastrophic fire.

\[\text{Figure 2.8. Excavated Areas on the Citadel Mound between 1900 and 2002 (Kealhofer 2005).}\]


\[28\] Ibid.
(destruction level). While the underlying Old Citadel of the Early Phrygian Kingdom filled with rich material culture was found to be well preserved because of the fire and reburying, the New Citadel of the Middle Phrygian Kingdom suffered greatly from the occupation of later inhabitants and looting. For these reasons, Young decided to uncover the Old Citadel to the Destruction Level where the level of excavation has remained today. The New Citadel was recorded prior to removal (See Fig. 2.8 for excavation areas dug between 1900 and 2002).

1950

Though the southwest trench was the first one to be dug on the Citadel Mound at Gordion by Machteld Mellink, the Citadel Gateway would not be uncovered until the 1952 campaign. This trench would be left open at the Persian level between 1950 and 1955.

1952

The Persian Gate building (today known as the Middle Phrygian Gate) of the New Citadel was uncovered by Young at the end of the 1952 season at the southeast side of the mound. In the area west of the Persian Gate, a deep cut was made to sample the

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underlying Phrygian level. Young described the construction of the structure as explained in his notes:

> It is built of brownish-gray limestone, not very hard, in roughly shaped blocks with characteristic tooling, probably made by the chisel, on their exposed faces. The blocks are laid in irregularly horizontal courses; the joints are not tight, and in many places the spaces between blocks – especially at the corners – are chinked with small splinters of the same stone. The space between the two built faces, inner and outer, is occupied by a filling of stone rubble.\(^{32}\)

1953

In 1953, during the fourth excavation campaign which began at the end of March until late July, the Early Phrygian gate was found and partially exposed.\(^{33}\) The entrance of the Phrygian gate was filled with rubble as a bed for the later Persian Gate. Its opening was sealed by a roughly built wall of dry stone. The rubble filling reached a depth of 9.5 meters from the top of the Phrygian wall to the paving of the gateway and parallel wooden logs (measuring up to four meters in length and 0.65 meter in diameter) were found laid perpendicular to the flanking walls in the rubble to prevent sliding down the slope of the ramp. The Phrygian gate wall displays a masonry bonded outer face, “the inner ends of the blocks of each course overhanging those of the course below…it is two courses in thickness, the stones of the outer course carefully laid though not tightly

fitted…the rubble filling behind must have been packed…course by course.”34 This bonded face was cleared to a depth of 4.5 m, approximately 15 courses below its preserved top. Young found the Persian Gate to have “suffered greatly from the passage of time.” Screen walls enclosed the area within the Persian Gate from the rest of the city creating an irregularly shaped inner court measuring 75 m in width by 50 m in depth.35

Young noted of the Early Phrygian Gate that:

...the Persian builders left standing those parts of the earlier building that underlay their own projected structure, and plundered the rest. The west wall of the north court, the west end of the wall between it and the passage, and the cross-wall of the gateway were stripped to their lowest courses. Many of the blocks taken from them were used in the construction of a dam-wall built to hold back the rubble bedding at the west. Plenty of blocks were available since the Phrygian building and the city wall to the north of it are built of a rather soft limestone which was dressed into roughly oblong blocks and laid in fairly regular horizontal courses. The blocks were not cut to an exact fit and the joints between them were chinked with slivers of the same stone. The surface of the masonry was covered with a coat of clay stucco, and this in turn seems to have been whitewashed36.

Most of the stucco was found to be severely damaged from the pressure of the rubble piled against it. The Persian dam wall was dismantled and the blocks were used to rebuild the foundation of the inner wall between the passage and the north court.

Six structures were discovered in the large court within the city gate including the Hearth Building, Buildings C, D, G, and F during the 1953 campaign. The “Painted House”

35 Ibid. 254.
36 Ibid. 257.
(later known as Polychrome House) was mentioned to be the most revealing of the buildings within this complex.\textsuperscript{37}

\textbf{1955}

The Polychrome House, immediately inside the Phrygian Gate complex, was excavated in 1955 and at this time given this name because of the blocks of bright red poros\textsuperscript{38} bedded on blocks of white poros found at its north wall and the hard slate-blue stone of the west and south walls. The building was discovered to be a four-sided trapezoid with a depth of 10.25 meters. At this time, Young thought that the building itself may have been used as an inner pylon or guardroom and the discovery of wooden floor beams and wooden posts suggested that the structure supported a roof,\textsuperscript{39} though one did not exist during the uncovering.

A stretch of the outer face of the Phrygian city wall was exposed to the north of the gate building during this season but its wall thickness was unknown. Also investigated was the point where the city wall meets the outer face of the North Court. This examination

\textsuperscript{38} Poros are variously defined limestones, occurring in Egypt and the Peloponnesus and extensively used as building materials by the ancient Greeks; apparently included several materials, such as tufa, travertine, fossiliferous limestone, and onyx marble (Getty Art & Architecture Thesaurus Online website: www.getty.edu/research/conducting_research/vocabularies/aat/).
showed a rough back outer face built of the same soft limestone blocks coursed, fitted, and finished like those found at the Phrygian citadel fortification wall.40

At the inner end of the Persian Gate-court, the “small pylon” (Polychrome House) was removed and “many tons and cubic meters of clay filling were removed”41 (Fig. 2.9). A portion of the north side of the gate structure was reconstructed by workmen on site.42

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41 Ibid.
Work was completed on a small scale and divided between the city mound, the lesser mound southeast of it, and the cemetery. The area within the main gate had been cleared in previous campaigns to the Persian (Middle Phrygian) level. Most of the structure at the Persian level had been plundered and only rubble bedding remained. The side courts (North and South Court buildings) of the Persian gate building were assumed to have a roof, supported by one or more wooden pillars to lessen the span of the roof and to create a more monumental approach to this area.\(^{43}\) Further excavations showed the remains of a

shallow porch foundation in front of the North Court building of the gate complex. At this time, Persian Building C was found to occupy the area between the South Court building and the structures found to the west.44

1957

The 1957 campaign exposed the eastern edge of a large Phrygian building called “Megaron 3”45 and discovered the Midas Tumulus, known today as Tumulus MM (Fig. 2.11).

Figure 2.11. Tumulus MM (Gordion Archives 1953).

By this time, the area immediately inside the city gate had not been cleared to the Phrygian level yet. Demolition of the Persian Building began in 1955 and was completed in 1957 in order to dig the area beneath it.\textsuperscript{46} This led to the clearing of the south side of the Polychrome House and the area immediately south of it but not deeper.

The uncovering of the connection between the Polychrome House and the South Court building revealed a nicely finished smooth masonry surface at the upper level of the terrace floor which was meant to be seen and a rough finish at the bottom of the South Court.\textsuperscript{47}

1958

The 1958 interim campaign was dedicated to a westward and southward expansion of the trenches in subsequently deeper excavation as well as stripping off the upper deposits of Hellenistic and Persian times to the level of the clay layer that lied on the burned Phrygian city. According to Young, both areas gave hope of important architectural remains and the south rooms of the terrace rooms were already known be full of Phrygian pots and other objects.\textsuperscript{48}

\textsuperscript{47} Ibid. 235.
\textsuperscript{48} Ibid. 227.
1959

The first objective during the 1959 season was to clear the remaining clay from Megaron 3. A portion of the north side of the Persian Gate was reconstructed by workmen on site.

1961

Though the first priority in 1961 was the final clearing of Megaron 3 (found in 1957 and largely uncovered in 1959) since it had not been completed in the last season, a large cut was also made at the northeast of the excavation in order to fix the line of the city wall to the north of the Phrygian Gate Building.

The Persian Gate’s north side was further cleaned and studied. Built of massive blocks, the north end of the structure was not intended to be seen as the blocks were not closely fitted or well finished whereas at the south end, the blocks were well dressed and fitted together but “interrupted at the level of every third course by horizontal wooden beams set into the face.” Calculations of the stair that lead to the rampart suggested a total of eighty steps of 15-18 cm in height over the span of a wall measuring 13 meters tall. The

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52 Ibid. 157.
north side of the Persian Gate Building was removed to enable examination of the underlying Phrygian remains.\textsuperscript{53}

In search for the junction between the Gate Building and the city wall, Dorothy Cox found the face of a “heavier earlier wall buried beneath the eighth century level” while cleaning the South Court building walls of the Phrygian Gate Building (date is now 9\textsuperscript{th} century).\textsuperscript{54}

Machteld Mellink returned to the southwest trench where it was left since it was first dug in 1950 to search for continuations of the earlier wall discovered by Cox as well as to look for the southward stretch of the Early Phrygian fortification. The stretches of the inner face of the early wall at the south and to the west of the South Court building were successfully found. They were built with “masonry faces inside and out and apparently with layers at intervals of cross timbers, was filled inside with rubble…had a thickness of approximately 8 m.” The Polychrome House is thought to be much older than the high gate beside it and was the original gateway that pierced the older fortification walls.\textsuperscript{55}

Upon discovering the cul-de-sac area of the Polychrome House and Court buildings of the gateway complex, Young’s theory was that the structures no longer served as the

\textsuperscript{54} Ibid. 167.
\textsuperscript{55} Ibid. 167-168.
main entrance when Gordion was burned. Neither North Court nor South Court buildings showed any signs of fire damage as seen in the other portions of the destruction level.\textsuperscript{56}

1963

Areas to be dug in the 1963 season were dictated by the plan of the Phrygian city at the Destruction Level, located 7 m below the surface of the Citadel Mound.\textsuperscript{57}

The fortification wall at the north side of the mound was apparently being used as a quarry for building stones. In the early 4\textsuperscript{th} century during Hellenistic times, the wall was in good repair but was most likely abandoned after the time of Alexander the Great in ca. 334 BC.\textsuperscript{58}

A bisecting wall was found at the center of the site separating the eastern location where the Persian Gate complex and Megarons existed and the western portion where Building A was found. Building A sits just south of the South Court building. Young postulated that there may have been another gate at the opposite side of the town (the northwest axis) to give access to the western side. After unearthing more buildings on the eastern side of the bisecting wall, the plan suggests that the Persian Gate complex opened out to

\textsuperscript{58} Ibid.
an enclosed courtyard with Buildings C, D, F, and G and then into another area beyond where Building H, M, O, and Q are situated. The North Court building “evidently fronted a street leading northeastward out of the small plaza, perhaps to a north gate.”59 The foundation of Building V was also found with the same orientation as the North Court building.

Young drew some parallels from a quick comparison of the Phrygian (Early Phrygian Old Citadel) and archaic (Middle Phrygian New Citadel) plans60:

- Both city gates lie at the southeast and consist of a central passageway with a court flanking at either side
- Both gateways give entrance to an inner court with two buildings facing from either side;
- The court is separated at its far end from the inner town by an enclosure wall with an opening decorated by a small propylon – the remains of the Phrygian propylon, which had been predicted, were cleared this year;
- Within the propylon a small square opened with two buildings facing it on the left (southwest), a single building at the right presenting a flank toward the open space and itself facing northwest – presumably to a street running northeast out of the square;
- The town is divided into eastern and western sectors, the archaic by a continuing wall, the Phrygian by the Terrace Building at a high level; and
- In the western sector, two parallel buildings or rows of buildings face each other across an open strip, probably a street, which seems to have run right across the town and perhaps to a gateway on the river side.

60 Ibid. 284.
The two phases were separated by a thick layer of clay of 2.5 to 4 m deep which showed a considerable difference in materials and technology used in their construction. The buildings at the archaic level (Middle Phrygian) were constructed of great squared blocks of hard limestone, gypsum, and andesite, none of which appear in the Early Phrygian settlement. Quarrying and finishing of these hard stones imply a considerable advance in masonry skills and technology beyond that required for shaping soft poros and sandstone used in the earlier Phrygian period.61

The blocks from an earlier structure found underneath the Northeast Building (Megaron 10) were discovered in the construction of a drain or water-channel that ran from the structure (near the southwest corner) and after a rather sharp turn terminates at the center of the Polychrome House. The drain was built to clear water from the courtyard that flooded during times of rain. A smaller drain was found in the passageway of the monumental Gate Building close to its inner corner at the south side in the cobbled pavement. The walls of this drain were apparently formed by laying two parallel large timber logs at a distance of 25 cm from each other.62 Since no earlier floor was found beneath the cobbled paving of the gate passage where the drain was located, Young

62 Ibid. 290.
believed that the drain was constructed at the same time as the Gate Building or at least before the cobbled paving was laid.63

Beneath the cobblestone paving traces of an earlier city gate were found. The inner face of the wall of the later Gate Building was found to rest directly upon an earlier wall which had a slightly different orientation – that of the Polychrome House. This construction was traced to a depth of 1.8 m below the paving of the gateway and described as:

*The masonry too was rougher and of different materials – layered courses of white poros, red poros, and yellow sandstone, each layer of three courses separated by a wooden balk set horizontally in the face of the wall.*64

This discovery indicated a straight line of axis for the entrance into the city of an earlier Gate Building and a slightly diagonal axis for the later structure constructed upon it (AJA 68 (1964) 291). At the conclusion of this excavation season, the Polychrome House was specified as the early gate with the city wall extending northeastward from it, covered by the North Court building of the later Gate Building. At the north is a square foundation with an orientation similar to that of the early gate and city wall.

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64 Ibid.
Work completed during this full scale excavation season was primarily focused on opening up toward the northwest of the Phrygian city and examining the stratification below its level at the northeast corner of the square. This is where Phrygian buildings found in 1963 were indicated to be in a poor state of preservation. Additionally, explorations in the neighborhood of the Great Tumulus (King Midas) were also conducted.65

1967

By this season, the Early Phrygian Destruction level containing the Citadel Gate was thoroughly excavated. The campaigns thereafter focused on other areas. In 1967, investigations moved northward to the river side of the mound, cutting trenches across the width of the city from southeast to northwest.66

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2.3 Conservation History

1956 – First Conservation Efforts / Concrete Capping

The earliest conservation efforts at Gordion were undertaken in 1956, only one year after its first excavation. Heavy rainfall during the winter had inevitably caused tremendous

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deterioration to the exposed structures excavated the previous year, specifically the Citadel Gate complex. A concrete capping was placed on the top of the gate building in 1956 to address the problem of water penetration. However, within a few years the capping, made of low quality cement, began to crack and spall,\(^{67}\) causing disintegration between the masonry core and veneer.\(^{68}\) It appears that a large area on the south side of the gate was never capped and remained uncovered and exposed to natural environmental conditions until 1989 when the 1956 capping was replaced by a new system.\(^{69}\) It was at first thought that the uncapped section lost the concrete above it from erosion. However, after inspection of numerous site photographs from 1957 it was determined that this area was left uncovered by the 1956 operation,\(^{70}\) probably due to lack of time at the end of the excavation season.

### 1974 – Conservation Attempts / Reconstruction of walls & Concrete capping

Following Young’s death in 1974, five conservation attempts were made at Gordion. These included the reconstruction of one of the walls on the southeastern gate complex.

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\(^{69}\) Rogers. 1989. 11.

\(^{70}\) Ibid. 16.
and the placement of a concrete capping at the top of the structure. These efforts were later considered inadequate as deterioration developed soon after completion.\(^{71}\)

1978 – Backfilling & Large Drain Reconstructed at center of Gate complex

By 1978, the condition of the site had rapidly declined and efforts to back-fill abandoned trenches that had increased in size from erosion and threatened collapse of nearby structures\(^{72}\) was performed throughout the site. In 1979 a large drain was reconstructed through the center of the gate complex\(^{73}\) to help divert rainwater away from the structure.

1986 – Glass tell-tales & Temporary Clay Cap

By 1986 it was apparent that the gate complex had become unstable, showing new large cracks in the masonry throughout the structure and the formation of a large protruding bulge found at the South Court building. At this time, glass tell-tales (pieces of ordinary window glass whose ends were plastered to either edges of a crack) were installed to determine movement of the protruding bulge (Fig. 2.14).\(^{74}\) The following year (1987), the tell-tales indicated that some cracks were active and could cause possible collapse of


the structure. Additionally, the poor condition was exacerbated by the continual water intrusion coming in from the top of the building through the fractured concrete capping and animals burrowed in the uncapped area on the south side of the gate. In response, a temporary clay cap was placed on the uncapped southern section of the gate to prevent further moisture intrusion until the entire 1956 cap was replaced the following year. Although these conservation efforts were made, other work conducted between 1978 and 1987 had not been completed due to lack of funding and available work staff during the off-season.

Figure 2.14. In 1986 glass tell-tales were installed to monitor movement of existing structures. Crack gauges below were later installed (Matero 2005).

77 Ibid.
78 Rogers. 1989. 16.
1989 – Old 1956 Concrete Cap replaced with New Cap

To combat the detrimental effects of weather and seismic activity which had accelerated deterioration and detachment of load-bearing veneer stones of the Citadel Gate, conservation measures were undertaken in 1989 during the first excavation season after Young’s death to improve the condition of the structure. The old 1956 concrete cap was removed from the gate building and replaced with an enhanced capping and drainage system that effectively eliminated water penetration into the walls (Fig. 2.15).

![Concrete Cap installed in 1989; note the separation between the concrete cap and the original limestone veneer (Matero 2005).](image)

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Though the water-proofing of the gate building was addressed by the end of this season, other concerns were not addressed such as “Youngian” and later trenches left open in need of back-filling and tending to other necessary matters at the rest of the site using the insufficient allocated site conservation money and staff.


In 1989, a monitoring system was established to evaluate the movement of the bulge found at the South Court building of the Gate complex. At unstable sections of the south wall, a series of masonry nails were set into stones at critical points (determined by laser theolodite) along the upper bulge and periodically checked to survey movement of stones within the structure. That same year, after consulting on the Midas Tumulus, architectural conservator Bernard Feilden recommends stabilized the Citadel Gate by grout injection in order to reestablish the bond between the veneer and core. Archie Walls from the UK also consulted on the stabilization of the walls of the Citadel Gate in 1990.

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82 Rogers. 1989. 17.
85 Ibid. 6.
In 1989, Mark Rogers of the University of North Carolina at Chapel Hill wrote “Site Conservation at Phrygian Gordion,” an Honors Essay for the Department of Art which discusses the site evolution, conservation history, and future conservation projects to be undertaken.87 In this report, Rogers elaborated the conservation problems found at Gordion correlated with poor archaeological practices. Problems stated included inadequate reconstruction of sections of the gateway that showed large gaps in the masonry almost forty years after which it was excavated that threatened to separate from the rest of the building.88

Between 1993 and 1998, Director of Architectural Conservation William Remsen recommended a site conservation program for Gordion based on a philosophy of structural and visual reintegration.89 Terrace Building 4 was selected as a pilot project to develop conservation techniques at Gordion. A sacrificial mortar cap at the tops of the existing walls were created with a layer of inert ground cover of crushed granite over a permeable layer of synthetic inorganic felt that prevented plant rootlets from entering. The goal for the sacrificial upper layer of mortar was to shed water and protect the lower original stone masonry with burned rubble core (of burned mud brick and burned reed).90

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88 Ibid. 11.
1999 – Introduction of Site Conservation Guidelines and Priority Program

As the new director of building conservation at Gordion in 1999, Mark Goodman introduced a set of formal site conservation guidelines and a priority program in the “Architectural Conservation at Gordion: Summer 1999” report based on the condition and significance of uncovered structures on site. The report suggested a three-part program consisting of a comprehensive Site Plan, Interpretive Program, and Site Maintenance.

1999 – Conor Power evaluates Citadel Gate

Conor Power, a structural engineer from Boston was selected in 1999 to evaluate the Citadel Gate walls. Power’s assessment of the gate complex indicated serious structural problems found specifically at the South Court building that had become dangerously unstable due to rotational slump and loss of integrity between the veneer and core. Power indicated that rotational slump was the product of shear forces found at the base of the structure that had fractured the load-bearing masonry and weakened the wall at that critical point; he warned of failure caused by outward collapse of the base. Additionally, loss of integrity between the limestone veneer and rubble core that had contributed to the bulge found at the South Court wall was the result of inadequate tying in of the core and veneer masonry during the original construction. Considerable bulging at approximately two-thirds the height of the wall was exacerbated by numerous factors, water intrusion from the top that resulted in “frost wedging” (freeze-thaw), erosion and displacement of
core material (earthen mortar, small chinking stones, rubble core), as well as other structural stresses such as seismic movements.\textsuperscript{91}

\textbf{1999 Early August – Power simplifies Monitoring System & indicates stability of structure}

In early August, with the help of archaeologist Richard Liebhart who was working on the conservation of the Midas Tumulus, Power simplified the 1989 monitoring system using plumblines to monitor movement of nails and other critical points along the bulge at the South Court building.\textsuperscript{92} At this time, Power indicated that the structure, with annular movements of $< 1.5$ cm, was stable enough until stabilization scaffolding was installed the following season.\textsuperscript{93}

\textbf{1999 August 16 – After Earthquake the Gate Complex considered dangerously unstable}

A few weeks later shortly after the 7.8 Magnitude earthquake on August 16, 1999, measurements taken showed significant movement (between 3 and 4 cm) at the center of the bulge and the displacement of several stones from the exposed section of the core near the west interior corner of the gate complex.\textsuperscript{94} At this time, the south wall was


\textsuperscript{93} Ibid.

\textsuperscript{94} Ibid.
considered dangerously unstable with the high probably of structural failure and major collapse after winter rains.\textsuperscript{95}

\textbf{1999 Summer – Goodman recommends stabilization techniques for the Gate building}

In response to Feilden’s 1989 recommendation to stabilize the Gate complex, Goodman acknowledged that grout injection was the best method for preserving its structural integrity at minimum intervention. In the Summer 1999 report, Goodman recommended effectively stabilizing the structure in four steps. The first step included the immediate installation of structural supports before any conservation work commenced through the construction of a well-drained earthen berm to bolster the base of the walls and the installation of a structural bracing system to support and provide access to walls using collapsible metal scaffolding. The second step involved injection grouting to restore the bond between the masonry veneer and core of the Gate complex. After grouting, the third step would be the remove and repack the upper sections of core masonry where large gaps were present within the wall that were caused by the detachment of veneer. And finally, Goodman recommended pinning into the veneer to tie into the core using

nonferrous elements such as fiberglass rods to further secure the bulge at the South Court wall.96

Due to insufficient funds to erect the proper structural supports required for any conservation work, efforts in the 1999 season focused on three tasks: continuation of the low-tech technique of plumbline measurements to monitor movements at the gate, installation of drainage and other preparatory work necessary for constructing the berm at the base of the walls, and recruiting a Turkish structural engineer to oversee the installation of the structural support system.97 Since the Citadel Gate was evaluated as the structure of highest priority at Gordion, stabilization and preservation was recommended and trial mortars for grouting would be tested at the nearby Middle Eastern Technical University (METU) conservation laboratory. It is uncertain if these laboratory tests were ever completed. Additionally, a Turkish engineer, Sureya Ural was retained to oversee the installation of the structural supports.98

2001 – Structural Scaffolding Erected at the Citadel Gate

When funds were finally secured for the conservation of the Citadel Gate at Gordion in 2001, installation of the supportive scaffolding began (Fig. 2.16) and Goodman established the structural grouting system first suggested by Feilden in 1989 through a

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97 Ibid. 7.
98 Ibid.
specialized technique known as “gravity grouting.” When properly applied, this technique uses the injection of grout (essentially liquid mortar) into the masonry core to consolidate and reestablish the bond between the veneer and core. This system involves raising a container of grout to utilize the force of gravity to inject the grout into the wall.\textsuperscript{99} In order to evaluate the efficacy and performance of this technique, the grouting was initially tested on a relatively stable section of the fortification wall south of the Citadel Gate in 2001.\textsuperscript{100}

\textbf{Figure 2.16.} Structural scaffolding at the Citadel Gate (Matero 2005).

Additional scaffolding was also installed for this grouting operation by reassembling the mining railroad originally used to excavate the site as well as a second railroad constructed on the scaffold called the “grout wagon” in order to transport the grout between the pumping stations and the wall.101

2002 – Grout Injection Introduced for Stabilization of the Citadel Gate

Between 2002 and 2004, Mark Goodman continued the structural conservation program at the Citadel Gate. Grouting began at the South Court Building of the Citadel Gate following successful grout trials in 2001. To document this process, digital photographs of the elevations were taken and photo-rectified to record “pre-consolidation” conditions and as visual reference for recording

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the quantity of grout used\textsuperscript{102} during each season.\textsuperscript{103}

2003 – Summer Site Report & Massive Structural (juniper) Timbers Found

The last Site Report produced in the summer of 2003 was written by Goodman which explained in detail the grout injection materials and techniques used to stabilize the Citadel Gate. The “gravity grouting” technique used gravity to develop pressure from a raised reservoir of grout above the injection point as a low-cost method (Fig. 2.17). The report stated that it was not uncommon to pump several 70 liter grout loads into one injection piper, simultaneously filling adjacent points. According to Goodman, this was desirable since it allowed effective filling of interconnected voids within the masonry core. In three seasons (2001, 2002, 2003) approximately 25\% (51 m\textsuperscript{2}) of the total area of the South Court and wall extensions were grouted. Although an inventory of purchased materials is enumerated in the table at the end of the report, the grout formulation used for consolidating the Citadel Gate is not clearly defined. Concerns of the continual increase in the structural voids while work progresses in addition to the periodic seismic activity led to the discussion of the need to further stabilize the structure through other repair methods such as structural pinning.\textsuperscript{104}


\textsuperscript{103} These digital photographs currently do not exist since they were stored on Goodman’s laptop which disappeared soon after his death in 2004 (Kenneth Sams (Director of the Gordion Archaeological Project, University of North Carolina at Chapel Hill). In discussion with the author, March 25, 2006).

Also noted in the 2003 report was the discovery of several structural timbers found at the eastern elevation of the south chamber which allows a better understanding of the original construction of the Citadel Gate complex. These massive timbers averaged in diameter between 20 and 30 centimeters, and were laid in the masonry core perpendicular to the eastern wall face to facilitate stabilization of the thick masonry core at critical points such as this one.105

2005 Summer – Conservation Field Visit

In the summer 2005 Frank Matero, the Chair of the Graduate Program in Historic Preservation at the University of Pennsylvania was invited by Kenneth Sams to conduct a site inspection of the conservation at Gordion. His review and assessment of past and current conservation efforts are found in the July 7, 2005 Field Report. The document discusses the value of Goodman’s tri-part architectural conservation program including conservation, interpretive, and maintenance programs, and states the importance of balancing conservation and interpretive programs while considering the input from stakeholders. Matero’s recommendations included the compilation of Site and Feature Conservation History Dossiers, an evaluation of the Citadel Gate grout formulation and stabilization methods through laboratory testing and remote sensing, the assessment of the performance of the temporary wall capping, conducting a building materials analysis to better understand the construction technology and improve conservation treatments,

use of digital recording for architectural and conservation documentation, designing a
visitor circulation with view station shelters and information panels, and investigation of
the slope stabilization and drainage control.106

2006 – Thesis Research & Field Investigation

The research conducted for this thesis is in advance of continuing the grouting of the
Citadel Gate. A field survey is scheduled for the summer 2006 by a conservation team
consisting of a Program Director, Supervising site conservator, two students from the
University of Pennsylvania, and two students from the Middle Eastern Technical
University (METU) in Ankara, Turkey. A condition assessment of the Citadel gate
complex as well as in situ testing of the grout used for the stabilization of the structure
will be conducted. Investigation of the Megarons is also planned for the upcoming
summer.

3.0 LITERATURE REVIEW

3.1 Research Parameters

Literature reviewed for this research included both published and unpublished works produced between 1982 and 2005. Publications came principally from Western Europe, with Italy, Greece, and the United Kingdom leading the research in traditional materials used in conservation and Belgium at the forefront in developing modern grouts for the stabilization of historic masonry structures. Articles from both the US and Germany were also included for this study. All published materials reviewed were in English, were primarily, but not limited to, articles from conference proceedings which stemmed from research conducted and supported by institutions and financed by both governmental and private organizations.

For a brief overview of the literature reviewed for this research and the techniques, materials, and applications studied, see Appendix A. Literature Review Matrix.
3.1.1 Keywords

Keywords used for this research included:

- absorption
- adhesion
- anchors (fasteners)
- bearing stress
- bonding
- brick dust
- building materials
- building pathology
- building stone
- compatibility
- compressive strength
- dispersion
- durability
- earthquakes
- fill
- flexural strength
- flow
- fluidity
- grout
- historic buildings
- hydraulic mortars
- injection
- injection grouting
- in situ testing
- lime
- lime-powdered brick
- mortar
- masonry
- consolidation
- masonry repairs
- mechanical pinning
- mechanical properties
- mechanical repairs
- mechanical strength
- mechanical test
- microstructure
- mortars
- multiple leaf walls
- non destructive testing
- permeability
- pinning
- pozzolan
- pozzolanicity
- reinforcement
- repairs
- replacement mortar
- rheology
- rubber masonry
- seismic
- shrinkage
- stabilization
- stone
- strengthening
- structural analysis
- structural stability
- technology
- test
- tomography
- unreinforced masonry
- ultrasonic
- ultrasound
- viscosity
- void filling

3.1.2 Definition

Grouting is the process of injecting fluids that set into cracks or voids used commonly to consolidate or strengthen a structural system.\textsuperscript{107} Grout is a thin mortar containing a considerable amount of water so that it has the consistency of a viscous liquid in order to be poured or pumped into joints, spaces, and cracks within masonry systems.\textsuperscript{108}

3.2 Performance Based Uses of Grouts and Grouting

A review of the conservation literature on grouts and grouting reveals a growing interest and popularity in the use of the technique in the past few decades. Attention and research of grouts used for the conservation of historic structures is specifically widespread in Western Europe, mainly in Italy and Greece where traditional masonry construction predominates. Grouts are used across a broad range of applications, from smaller reattachment of plaster finishes to larger projects using injection grouting for structural consolidation. Project parameters, whether small scale or large scale application, normally dictate the type of constituent materials used in grout formulations as well as the techniques used for their application. The literature review in the following section is divided into two sections based on their use (civil engineering vs. conservation). The first section describes materials, techniques and research generated by the art and architectural conservation community generally for non-structural repairs; the second section describes the practice of injection grouting for larger scale stabilization of historic masonry structures, generally conducted by the engineering community. Further explanation of hydraulic lime grouts and additives as well as their use in conservation is presented at the end of this section. Since grouts are essentially liquid mortars, literature pertaining to the study of mortars consisting of similar materials (e.g. lime, sand, and brick dust) used in the formulations for the laboratory testing program has been included in this review.
3.2.1 Art and Architectural Conservation

The gradual discovery of the detrimental effects of past masonry conservation repairs, often employing Portland cement to traditional historic structures in the past few decades has caused a concern in the art and architectural conservation community. This concern has led to a growing body of research in traditional materials such as lime-based grout formulations, and other admixtures in order to better understand the consequences of their use and their compatibility with the existing historic fabric.\textsuperscript{109} Additionally, their research also hopes to define guidelines, set performance standards, and provide new and improved formulations through laboratory and field testing.

1979-1984 ICCROM – Plasters & Floor Mosaics

Between 1979 and 1984, an extensive research program financed by the European Economic Community (EEC) and UNESCO grants was undertaken by ICCROM (the International Centre for the Study of the Preservation and the Restoration of Cultural Property) to develop and test grouts used for the reattachment of lime mural plasters and floor mosaics.\textsuperscript{110,111} Their research began with the study of several formulation materials including Portland cement, lime, lime-cement, and hydraulic additives in order to confirm


their effect on the performance characteristics of grouts. Their proposed critical mechanical and physico-chemical properties for testing and evaluating grouts and mortars for conservation are still applicable today; these include workability, set time, shrinkage, compressive and flexural strength, modulus of elasticity under compression, adhesion, thermal expansion, soluble salts, weathering resistance, porosity, pore-size distribution, and water absorption. A set of ideal performance specifications for grouts composed of hydraulic lime binders (specifically Lafarge Chaux Blanche) was established that emphasized the importance of set time, shrinkage, mechanical strength, permeability, extractable residue, and tackiness.

1986 House of Meanander, Pompeii, Italy

In 1986 study and treatment of the peristyle garden wall and its murals at the House of Meanander at Pompeii, Italy was undertaken utilizing a grout formulation based on the ICCROM. A grout composed of a moderately hydraulic lime (Lafarge Chaux Blanche) and brick dust modified with an acrylic emulsion admixture (Primal AC 33) and barium hydroxide was used to reattach over 60% of the entire surface area by injection

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113 Ferragnani et al. 1984.

through cracks and other openings on the surface. This proved to be a successful formulation and technique for consolidating the historic fabric.

1986 Hadrian’s Wall, 1994 Smeaton – Effects of Brick dust in Lime-based mixtures

As a result of the experimental work on mortars conducted by English Heritage in 1986 on the conservation of Hadrian’s Wall in northern England, the Smeaton Project was developed to address the issues of mortar analysis and the components of historic mortars, performance criteria, and mortar preparation and utilization. Though this case study researches the properties of mortars rather than grout, its use of lime-sand-brick dust mixtures makes it an important and applicable study for the experimental laboratory program in the current research. The Smeaton Project research program was a joint project between ICCROM, English Heritage (the Historic Buildings and Monuments Commission for England), and Bournemouth University. The project was initiated in response to the detrimental effects of Portland cement repairs used at the Hadrian’s Wall. Because of its impervious nature, Portland cement was found to cause concentrated wet-dry cycles, trapping water within the already weakened masonry core, increasing the risk of frost damage, and possibly causing mechanical damage to the stone when the high-strength mortar was removed during maintenance. Upon these discoveries, a testing program was begun to develop appropriate conservation mortars based on alternative

116 Ibid.
117 Ibid.
formulations. The five year program tested and compared lime-based mixtures with the addition of brick dust and Portland cement.

Results from laboratory and field testing showed the critical effects of brick dust in lime-based mixtures based on three factors: the firing temperature of the bricks, particle size, and proportions of lime, sand, and brick dust used in a mixture. Brick dust particle sizes ranging between 75μm and 300 μm were tested. “Low fired” brick dust from bricks fired at a temperature lower than 950°C showed increased strength and durability in lime-sand-brick dust mixtures. \(^{118,119}\) This was more pronounced when a higher proportion of brick dust, with smaller particle sizes < 75μm, was used in the mix. Mixtures using low fired brick dusts also tended to harden slightly more quickly than others.

Additionally, the smaller particle size brick dust, acting as a pozzolan, reacted with the lime and accelerated setting and produced a higher strength hydraulic mortar. Test results for moisture content also revealed that when smaller brick dust particle sizes were used, less water was needed in mixing which assisted in preventing shrinkage.


The larger particle size brick dust $> 300\mu m$ acted more as a porous particulate and possible air-entraining additive which aided in carbonation and improved resistance to frost and salt crystallization. Porosity appeared to be more significant than firing temperature for the larger particle size brick dust used in the lime-sand mixtures. The mix ratio which proved most successful in the experiments was 1:3:1 (by volume) of lime:sand:brick dust.$^{120}$ This research forms the basis for the current research laboratory experimental program.

3.2.2 Grouts in Civil Engineering for Historic Masonry Repairs

Large scale projects primarily encompass the work of consolidating historic masonry structures to prevent structural failure and collapse. One major concern that tends to arise frequently in the literature on grouting used for stabilizing historic structures is the importance of the compatibility between the grout and the existing structural system. According to the reviewed literature, project parameters for strengthening historic structures need to address four key issues: compatibility between the existing fabric and the grouting material, water introduced to the masonry system should be minimized to reduce degradation of the original structure, soluble salts should be not be introduced and

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salts already extant should be stabilized, and the mechanical strength of the new grout should be less than that of the original wall mortar.\(^{121}\)


As a response to the major earthquakes in ex-Yugoslavia in the 1960s and the 1976 Friuli earthquake, retrofitting of rubble and multiple-leaf\(^{122}\) walls (Fig. 3.1) by injection grouting became a priority and research focused on the areas affected by seismic activity in continental Europe. An extended research program developed through the collaboration between the Politecnico of Milano, the University of Padova, and ITEA, a Province of Trento bureau for public housing, defined the appropriate guidelines for the optimal choice of injection grout admixtures for the repair and strengthening of masonry structures in seismic areas.\(^{123}\)


\(^{122}\) Multiple-leaf walls refer to assemblies constructed of more than one wythe thick masonry, usually with two veneer stone faces and a rubble core. However, several different types exist (see Fig. 1).

1990 – Performance / Durability of Grouts for Strengthening Masonry Structures

A scientific study prepared in 1990 by the Politecnico of Milano showed the continuation of experimental research on the performance and durability of grouts for the strengthening of historic masonry structures. In this case a set of new standardized test processes was developed to measure the effectiveness of epoxy resin grouts. Though this study tested epoxy resin grouts, conclusions of previous studies conducted by the same authors showed that efficacy of injections using a variety of materials including hydraulic lime mixtures, were dependent not only on the physico-chemical and mechanical compatibility of the grout and the original material, but also the penetration and diffusion capacity of the grout. For instance, in the 1987 study a pozzolana-lime-sand grout (1:4:9.28 by volume) displayed very low cohesive strength and confirmed the

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incompatibility of the mixture with the original brick material. These studies indicated that successful grouting was a result of using an adequate injection technique with constant injection pressure for filling masonry voids.

Conducted throughout the 1990s, these studies focused on the need for selecting the appropriate grout formulation (organic and inorganic) in order to meet chemical, physical, and mechanical requirements for compatibility with existing historic fabric. Grouts considered appropriate possessed characteristics of good penetration under low pressure, displayed adhesion and chemical compatibility between existing and new materials, met minimal mechanical strength and deformability, and behavior responded to seismic activity. In order to evaluate the efficacy of the selected grout, a control sequence was used for first understanding the wall morphology – the physical, chemical, and mechanical properties of all components of the wall system through in situ investigation and testing, the detection of injectibility of grout tested in the laboratory and in situ when applied to an experimental problem, and finally, the evaluation of the effectiveness of the intervention using non-destructive testing including ultrasonic, sonic vibrational, and flat-jack techniques.  

2000 – Consider Structure before Grout

It is thus, important to analyze the existing structural system as a starting point for defining any requirements for stabilization including grout formulations. A study conducted by the collaboration of the Catholic University of Leuven in Belgium and National Technical University of Athens in Greece defined design requirements for injection grouts used for consolidating ancient masonry based on rheological and mechanical properties. Structural requirements consequently inform the requirement of the materials and their ratios used for grouts as well as their compositions. Grout requirements concerning the physical behavior of the injected structure include injectibility, adhesion with the existing masonry components, and sufficient mechanical properties within a defined span. Those requirements relative to the durability requirements of the injected structure include compatible microstructure, bonding with existing materials, and properties of the raw materials.128 The study tested several lime-cement formulations with trass and fumed silica and found that compositions containing little Portland cement developed sufficiently high mechanical properties, initially from the cement and fumed silica the continuation of the pozzolanic reaction for a long period. And though the grouts showed high bond tensile strength, their shear strengths were only average; adhesion between the grout and brick were much higher than between limestone and grout due to the smoother surface of limestone and the higher porosity of the brick.

Grout porosity was also found to be higher than that of the original hydraulic mortars, even after 180 days; porosity and pore size distribution appeared to be the result of water content used in the mixture, not the fineness of the materials. Fineness combined with the mixing procedure both contributed to the penetrability of grouts. The study also revealed in microstructural observations the pozzolanic reaction and progressive densification of the grout over time. Due to the slow curing of these lime mixtures, the author acknowledged the importance of careful in situ execution and that the study of mixed type binders be followed for long periods of time, past the 90 and 180 days conducted for this study, under different curing conditions, in order to really understand the advantages and disadvantages of such grouts.129

2000 – Non-destructive In Situ Testing

Since the current state of non-destructive testing is hardly able to map major cracks in masonry structures, research on grout injection has also paid attention to the method of reliability analysis to discover the parameters that influence the probability of failure. Approaches have included calculating “global permeability value” for each injection hole through a mathematical code and understanding the interaction between the masonry properties and grout properties during the injection process.130 Additionally, the


recognition for the need for safety assessments for unprotected historic monuments has led to some probabilistic techniques for evaluating uncertainties for parameters such as strength, actions, geometry, and model uncertainties, resulting in a value for the probability of failure.\textsuperscript{131}

3.3 Composition Based Uses of Grouts and Grouting

3.3.1 Hydraulic lime based Grouts

Materials found in previous research have ranged from traditional hydraulic lime based mixtures\textsuperscript{132,133,134} with the addition of brick dust,\textsuperscript{135,136} pulverized ash and bentonite,\textsuperscript{137} or more recent additives such as superplasticizers and microsphere fillers\textsuperscript{138} to recent adaptations of cementitious mixtures with modern materials such as superplasticizers and

fluidizers as well as fumed silica. See Appendix A. Literature Review Matrix for formulations found in the literature. There is a growing trend in the current research to test behaviors of mixtures that combine both traditional and modern materials in hopes of finding formulations which are compatible with historic masonry structures. Lime, natural pozzolans, ordinary Portland cement, and silica fume were materials selected in a previous testing program based on the defined performance criteria of consolidating ancient masonry: the physico-chemical compatibility (i.e. durability) of the newly introduced materials in the grout formulation with the existing fabric and the performance criteria for the improvement of mechanical strength of the masonry.

In the United Kingdom, lime-based mortars with hydraulic additives remained forgotten after the Roman occupation until Smeaton’s research in the late eighteenth century. With the arrival of Portland cement in the nineteenth century, lime-pozzolan mixes disappeared again until recently when the need to restore and conserve ancient buildings was considered a higher priority.

141 Ibid.
The widespread use of Portland cement in the building industry spurred interest in architectural conservation because of its early set and strength, high ultimate strength and durability, low permeability, wide availability, and relative low-cost. Introduction of other modern materials such as synthetic resins replaced lime in grout mixtures because of characteristics traditional materials could not compete with, like the ability to resist weathering. However, awareness in the late 1970s within the architectural conservation community of the detrimental effects of Portland cements used in conservation repairs resulted in an increasing repudiation of hydraulic binders among professionals and a renewed interest in the research and use of original formulations (e.g. lime and pozzolanic additives) found in ancient structures as a more compatible and sustainable approach to the protection of cultural resources. Portland cement is not necessarily a poor material; it performs well when applied in the appropriate situation. However, its rigidity, density, impermeability, and other seemingly advantageous characteristics are rather incompatible with softer, highly elastic, and porous historic mortars and masonry systems. For instance, when masonry becomes saturated in the surrounding areas of localized repairs using cement, the masonry cannot release the water and in turn the bond between the new and old materials fails.

The primary advantage of a lime-based grout is thus, its compatibility with traditional masonry structures. Its relative weak strength is comparable to the strength of the adherent mortars. Lime is also a viscosifying agent and considered important for the stability of a grout.\textsuperscript{145} In addition, its permeability and resistance to salts and sulphates make it a more flexible material in comparison to cement. However, the carbonation process of lime in thick historic walls is often very slow and may prove to be too slow for practical and safety concerns. And although pozzolans are known to assist in final strength in lime-based grout mixtures, their initial strength remains unaffected. Another great disadvantage is the high volume of water required for injectible lime grouts, which not only produces weak grout but also decreases the initial friction on the existing masonry structure and is thus, considered to seriously endanger the structure.\textsuperscript{146}

3.3.1.1 Hydraulic lime

Two types of limes are used in architectural conservation: high calcium lime – a high purity material produced from the calcinations of high purity limestone and hydraulic lime, produced by calcining impure limestone usually at higher temperatures. At high temperatures, the silica, alumina, and iron in the impure limestone react with the lime to create cementitious materials which react with water and give its set and ultimate

\textsuperscript{146} Ibid. 368.
The combination of the hydration of the cementitious materials together with the normal carbonation reaction shown in high calcium limes gives the setting and hardening of hydraulic limes. The lime used in the testing program for the current research, Lafarge Chaux Blanche is a moderately hydraulic lime (NHL 3.5-Z).

Hydraulic lime is derived from limestone that naturally contains clays as well as a majority of calcium carbonate (CaCO₃) and of magnesium carbonate (MgCO₃). The “hydraulic” property – the ability to set and harden by chemical reaction with water and without air – is accomplished after calcination at high temperatures (near 10,000°C / 18000°F). Quicklime results from this calcination process which consists of oxides of calcium (CaO) and magnesium (MgO). It is called quicklime because of its rapid reaction with water and simultaneous release of heat. Hydrated lime is produced by combining quicklime with a controlled quantity of water to convert the oxides to hydroxides, Ca(OH)₂ and Mg(OH)₂. In this process, all the water is chemically combined with the quicklime and a dry, fine powder is produced. Too much water results in lime putty. The combination of changes in firing temperature and the constituents in the limestone (e.g. impurities like iron and sulfur) may produce hydraulic limes of varying characteristics. Natural pozzolanas such as volcanic ash and trass and additives such

148 Ibid. 36.
as brick dust are known to produce a hydraulic set because of their reactive silicates. Lime cures by absorption of carbon dioxide from the air, forming calcium carbonate or magnesium carbonate. Today, hydraulic limes are available mainly in England and France and rarely found in the United States.

There is currently one known commercial supplier of hydrated hydraulic lime in the United States, Transmineral America located in California. Though the commercial hydrated hydraulic lime used in this Master Thesis research *Chaux Blanche* is produced by Lafarge France, its regional offices in the United States, Lafarge North America do not carry the product.

### 3.3.1.2 Pozzolanas

Interest over the past decade in the pozzolanic reactions between hydrated lime and crushed brick has been the result of the desire to better characterize historic mixtures, to produce new pozzolanic ingredients, and the need to stabilize masonry structures requiring formulations that are compatible with the existing materials and perform as grouts.

Since Roman times, natural pozzolans such as low fired brick dust were used to obtain hydraulic properties in building materials. There are two types of pozzolans, natural and artificial. Natural pozzolans such as volcanic ash, Tripoli, diatomaceous earth, and
pumice dust\textsuperscript{150} do not require treatment when used. Artificial pozzolans, on the other hand, can obtain pozzolanic properties when thermally treated which transforms their primary nature. They are the consequence of chemical and/or structural modifications made to their original material which assumed little or no pozzolanic characteristics.\textsuperscript{151} Artificial pozzolans include pulverized blast furnace slag, fly ash/pulverized fuel ash (PFA), ground brick or tile, kaolinite, and high temperature insulation (HTI).\textsuperscript{152}

Though it is known that hydraulicity is acquired from the pozzolanic action of brick powder on hydrated lime, there are other beneficial properties found in broken and powdered brick including acting as an anti-shrinkage agent, improving binding and adhesion with aggregates, and enabling deeper penetration of CO\textsubscript{2} by improved porosity, leading to greater depth of hardening.\textsuperscript{153}

Extensive studies on the use of powdered bricks on hydrated lime formulations have been conducted by the Politecnico di Milano, the same authors working on the retrofitting of historic masonry structures discussed in the previous section. One study tested the roles of large brick pebbles and brick dust used in formulating hydrated lime mortars and found that the large size particles contributed to early deformation of the masonry caused


\textsuperscript{152} Boffey and Hirst. (1999): 36.

\textsuperscript{153} Ibid. 38.
by creep and shrinkage in the mixture and the very slow development of carbonation and pozollanic action.\textsuperscript{154} Subsequently, a study of the pozollanicity of bricks and clays also produced results lauding the use of low-fired bricks in hydraulic mixtures. The study concluded that the use of finely powdered bricks contributed to a good degree of hydraulicity in a mixture as long as the bricks were pozollanic (low fired, clayey material), exemplifying the durability of ancient mortars tested in this research.\textsuperscript{155} In 1999, a study on the use of pozollans in lime mortars conducted in the United Kingdom acknowledged the problem with the lack of performance data for the wide range of materials known to have pozollanic properties. In hydraulic lime mixtures especially, the faster setting and final strength achieved by using pozollanic additives could produce a less desirable long-term effect, that of shrinking and cracking.\textsuperscript{156}

3.3.1.3 Modern Additives

Popularity of microspheres in grout mixtures as a light-weight substitute for aggregate is a rapidly increasing practice seen mainly in the research and studies conducted by institutions because of their novelty. For instance, the reattachment of lime plasters on earthen supports was treated with a grout based on hydrated hydraulic lime, white quartz sand, microspheres, and acrylic emulsion developed by the Architectural Conservation

Laboratory at the University of Pennsylvania. Another lime-based grout composed of hydrated lime, local sand, fumed silica, a superplasticizer, and ceramic microspheres, developed at Columbia University’s architectural conservation laboratory in New York was used for the conservation of the 4th century B.C. ruins of a Hellenistic farmhouse in Crimea, Ukraine. Other materials such as superplasticizers are used for temporary fluidity to improve injectibility and pozzolanic additives such as fumed silica and trass are used to increase the hydraulic reaction of the lime-based mixtures.

### 3.3.2 Cementitious grouts

The focus on traditional materials used for research is prevalent in the fields of art and architectural conservation. However, review of the civil engineering literature on historic structures revealed the common use of cementitious grouts for consolidating masonry structures. Some consider this to include cement and lime-based blended grouts. Grouting by injection of polymers, resins, and cementitious grouts for the repair and

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strengthening of masonry structures is widely practiced in Europe, particularly Italy.\textsuperscript{161}

There are certainly more sensitive approaches than others.

From the use of pure concrete mixes of Portland cement for the stabilization of a rubble masonry foundation of the Qutb Minar in India\textsuperscript{162} to combination mixtures of cement with pozzolanic additives for crack repairs in brick\textsuperscript{163} to cementitious mixtures with bentonite, fly ash, and superplasticizers for structural consolidating historic masonry systems,\textsuperscript{164,165} it is apparent that cement is ubiquitous in the industry. However, more sensitive approaches can be seen in the engineering community through the adaptation of concrete mixtures combined with traditional materials like lime for the conservation of masonry structures. For example, designed grout formulations composed of lime, pulverized fly ash, and bentonite proposed for the stabilization of rubble-filled walls,\textsuperscript{166} mud grouts modified with fly ash and lime for strengthening adobe walls at Mission Pio

\begin{footnotesize}
\begin{itemize}
\item\textsuperscript{166} Ibid.
\end{itemize}
\end{footnotesize}
Pico,\textsuperscript{167} and use of Microlite, a commercial product consisting of microfine cement and additives for the repair of double wythe tuff walls under seismic activity in Italy\textsuperscript{168} show the range of combination mixtures using both modern and traditional materials for the strengthening of historic structures.

3.4 Alternative Repair Methods

1990s-Present

Innovative designs have also permitted explorations of using modern materials within a historic setting. For instance, using reinforced concrete isolated from old masonry by a layer of lime to prevent the hard and impervious concrete from coming in direct contact with the original masonry fabric would strengthen the historic masonry at the same time provide flexibility for differential movement of the two independent materials.\textsuperscript{169}

Stabilization of historic masonry structures have also been addressed in several other ways instead of grouting. These methods depend on both the present defects and weaknesses found during the site investigation and the mechanism causing the deterioration and failure. Among these techniques are pilings developed for underpinning structures with minimum intrusion to the surrounding strata for distributing


load,\textsuperscript{170} stitching or mechanical pinning of masonry structures where cross walls are not bonded into the external walls to restore stability, chemical anchoring systems using stainless steel rods fixed with epoxy resins,\textsuperscript{171} and similar alternative systems using stainless steel rods within fabric sleeves which are grout injected to fill the shape of the voids to provide positive bonding with the masonry structure.\textsuperscript{172} For further discussion on alternative methods for stabilizing masonry structures, see Section 6.2 Alternative Repair Methods in the Structural Analysis & Repair Methods chapter.


\textsuperscript{171} Ibid.

4.0 LABORATORY TESTING PROGRAM

4.1 Methodology

This laboratory testing program is the first of two phases designed to measure the physical-chemical properties as well as to evaluate performance characteristics of three grout formulations for use in consolidating the rubble core veneer-stone masonry system of the Early Phrygian Gateway at Gordion, Turkey. Phase I includes the assessment of the plastic state of the three grout formulations and preliminary findings of the grout at 28-days curing. The testing program for Phase II, intended for future work once more information is gathered from the site investigation scheduled for this Summer 2006 and after full cure, is outlined at the end of this section (See Section 4.5 Future Testing).

The three grout formulations tested are based on what has been previously specified used to consolidate the Early Phrygian Gate at Gordion, Turkey. Though this phase evaluates mainly the plastic state of the grout formulations, Phase I also includes the preliminary results of the splitting tensile strength test conducted on specimens after a 28-day cure. This work lays the groundwork for future laboratory and site testing by identifying the specific performance criteria necessary for the grout and its contribution to structural stability of the Citadel Gate masonry. Extra laboratory specimens of the three grout formulations were produced in Phase I for future testing (at 180 days cure) in Phase II for both physical-chemical and mechanical properties.

An additional and final phase in the future could ideally encompass a design program in treating the specific conservation problems of the masonry as designing alternative methods for stabilizing the Citadel Gateway.

### 2.1.1 Performance Criteria

The primary performance criteria used to evaluate the grout formulations, according to the literature review and project parameters specified for grout injection at the Gateway include:

1. Adequate fluidity in the liquid phase to fill voids by low pressure injection to penetrate rubble masonry core;
2. Minimal segregation and shrinkage while producing compositional stability until set to effectively consolidate the masonry structure;
3. Hydraulic set within a reasonable setting time to resist displacement of the masonry and allow for proper cure;
4. Minimal shrinkage between the liquid and solid states;
5. Low density;
6. Chemical and physical compatibility with the material to be consolidated; strength should be within the range of the historic material; and
7. Good adhesive bonding to adjacent surfaces and shear strength to resist differential movement caused by seismic activity.
4.2 Selection of Materials and Formulations

Grouts derive their character from the properties of the individual components used in the formulation. It is important to understand the interactions between the various materials as well as their chemical, mechanical, and physical compatibility with the original material or systems under anticipated environmental conditions. Grouting formulations are comprised of three basic components: binders, aggregates, and dispersant (water). On occasion, additional components such as additives or thickeners are used to supplement the grout and/or to meet specific requirements. It is critical to thus, formulate a grout that balances all components in the proper proportions in order to achieve the desired properties established by the performance criteria of the project. For the current research, a moderately hydraulic lime-based grout is the formulation selected, as specified by the project parameters for the Early Phrygian Gateway at Gordion, Turkey, and composed of the following ingredients:

4.2.1 Binders

The properties and performance of the grout in the cured state are determined primarily by the binder. Only one binder, Lafarge Chaux Blanche hydrated hydraulic lime was tested due to its previous selection by site conservators at Gordion and its availability in Turkey.
4.2.1.1 Lafarge “Chaux Blanche” hydrated hydraulic lime (HHL)

The natural hydraulic lime used for the experimental laboratory testing program was manufactured by Lafarge France (Ciments division) and obtained from the Middle East Technical University (METU) in Ankara, Turkey through a shipment in January 2006. Lafarge natural hydraulic limes (NHL) are produced by burning (at 1200°C) and slaking of limestone with a siliceous content. According to the manufacturer, the product strictly conforms to French Norm standard NF P 15-311 and European Norms standard EN 459-1 classifying NHL. Chaux Blanche is a “moderately hydraulic” lime with an average compressive strength of 194 psi at 28 days for a 1:3 (lime:sand) ratio and meets the requirements of ASTM specification C141-85 “Standard Specification for Hydraulic Hydrated Lime for Structural Purposes.”

Several formal systems exist for expressing the hydraulic value of a cementing material. The hydraulic index classifies hydraulic lime into two groups depending on the ratio of silica plus alumina to the percentage of lime. The index indicates the higher the silica and alumina content, the greater the hydraulicity. “Feebly hydraulic” has a hydraulic index between 0.10 and 0.20 and “eminently hydraulic” had a hydraulic index between 0.20 and 0.40.174 The cementation index, used by the cement industry is like the hydraulic index. It not only takes into account silica and alumina content but also the magnesia and iron oxide found in lime. “Feebly hydraulic” is defined by the cementation

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index as products with an index ranging from 0.70 and 0.30 and “eminently hydraulic”
products with an index ranging from 0.70 and 1.10.\textsuperscript{175} Michael Wingate uses an index
based on set times, where “feebly hydraulic” as setting between 15-21 days, “moderately
hydraulic” as setting between 5-15 days, and “eminently hydraulic” as setting between 1-4
days.\textsuperscript{176} Wingate does not specify under what conditions, whether under water, at high
humidity, or in open air, these set times are based. Table 4.1 presents a summary of
terminology for building limes according to EU Norm EN 459.\textsuperscript{177}

\textbf{Table 4.1. Summary of Terminology for Building Limes according to EN 459.}

\begin{tabular}{|l|l|l|}
\hline
\textbf{Hydraulic Lime} & \textbf{OLD} & \textbf{NEW} & \textbf{Natural hydraulic lime (NHL)} \\
\hline
Eminently Hydraulic & & NHL 5 & NATURAL HYDRAULIC LIMES \\
Moderately Hydraulic & & NHL 3.5 & Argillaceous or siliceous limestone burned and slaked. Reduced to powder with or without \\
Feebly Hydraulic & & NHL 2 & grinding. NO ADDITIONS ALLOWED \\
Artificial Hydraulic Lime & Hydraulic Limes & HL & A blend of calcium hydroxide, calcium silicate and calcium aluminates \textit{(and possibly other material such as ash, filler, etc.)} \\
\hline
\end{tabular}

\textsuperscript{177} St. Astier website: www.stastier.co.uk
According to Lafarge France, the natural hydraulic limes are burned and slaked argillaceous or siliceous limestone which are reduced to powder with or without grinding. Additions of suitable pozzolanic or hydraulic materials (up to 20%) made to the natural hydraulic limes are designated NHL-Z. NHL and NHL-Z products can contain organic additives in small quantities without harmful effects on the properties. Natural hydraulic lime products produced by Lafarge France Ciments are commercially advertised for use as coatings, whitewash, mortar, and injection grouting.

Lafarge *Chaux Blanche* is an NHL 3.5-Z. The product has seen widespread use in experimental laboratory programs in past research, especially throughout continental Europe. The hydrated hydraulic lime has shown lower strength and alkali content than other hydraulic limes and lower alkali content in comparison to Portland cement, making it suitable for grouting. Lafarge hydraulic limes used in past studies have tested grout performance for consolidating ancient masonry, quantified mechanical and physico-chemical characteristics of traditional mortars, and more specifically used Chaux Blanche for reattachment of lime plaster and mosaics.

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181 D. Ferragni et al., 1984.
4.2.1.2 Crushed Brick < 75 μm, low-fired (B)

Bricks used for the source of brick dust for the laboratory testing specimens are 18th century low fired brick (firing temperature not specified) from San Antonio Bastion in San Juan, Puerto Rico. The bricks were recycled, crushed, and sieved and sent separated in seven different particle sizes (passing particles < 475-75 μm) to the University of Pennsylvania by the National Park Service, San Juan National Historic Site Crew in Old San Juan. Only the brick dust sieved through a No. 200 ASTM standard sieve (passing particles < 75 μm) was used in the laboratory testing program for the current research.

Present research has shown that smaller particle sized brick dust (< 75 μm) in a lime mortar or grout acts as a pozzolanic additive accelerating setting time and achieving higher strength. Larger particle sized brick dust is used to improve resistance to frost and salt crystallization and enhance carbonation since it acts more as a porous particulate and air-entraining additive. Brick dust also has been shown in previous research to

reduce shrinkage.\textsuperscript{185} The disadvantages are its color and the size which is generally not available in the fine mesh grade.

4.2.2 Aggregates and Fillers

Aggregates and fillers are used in cementitious admixtures to reduce shrinkage, control strength, adjust fluidity, and reduce cost. Yellow bar sand was the aggregate selected for use in all grout formulations produced for the laboratory testing program. The brick dust included in specified grout formulations was used as a pozzolanic additive in the current research based on its previous use at Gordion.

4.2.2.1 Yellow Bar Sand < 1000 μm, angular ~ sub-angular (S)

All grout formulations in the current research were mixed with Yellow Bar Sand, purchased in January 2006 from a local Philadelphia supplier Cava Building Supply. According to the manufacturer, this sand meets ASTM C144-99 “Standard Specification for Aggregate for Masonry Mortar.” The sand aggregate selection was based on finding one similar to the local sand (Belikopru 0-1mm)\textsuperscript{186} previously specified for injection grouting of the Citadel Gate at Gordion. The particle size distribution of the Yellow Bar Sand, shown in Table 4.2 and illustrated in Graph 4.1 below, was determined according to ASTM C136-01 “Standard Test Method for Sieve Analysis of Fine and Coarse particles.”


Aggregates.” The sand contains approximately 97% of its mass between 0 and 1000 μm in size and has less than one percent fine particles below 75 μm and is considered a well-graded sand.\textsuperscript{187} Visual examination of the Yellow Bar Sand determined it to be “sharp sand” with angular and subangular particles, which is generally considered the best sand for mortars.\textsuperscript{188} For use in this research, the sand was first dried in the oven at 60ºC for 48 hours, cooled, and sieved through a No.18 ASTM standard sieve (passing particles < 1000 μm).

Table 4.2. Particle Size Distribution for Yellow Bar Sand

<table>
<thead>
<tr>
<th>ASTM Sieve Number</th>
<th>Screen Size (μ)</th>
<th>Weight Retained (g)</th>
<th>% Retained</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2360</td>
<td>0.90</td>
<td>0.3</td>
<td>99.7</td>
</tr>
<tr>
<td>16</td>
<td>1180</td>
<td>7.26</td>
<td>2.42</td>
<td>97.28</td>
</tr>
<tr>
<td>18</td>
<td>1000</td>
<td>2.02</td>
<td>0.67</td>
<td>96.61</td>
</tr>
<tr>
<td>30</td>
<td>600</td>
<td>26.87</td>
<td>8.96</td>
<td>87.65</td>
</tr>
<tr>
<td>50</td>
<td>300</td>
<td>139.53</td>
<td>46.51</td>
<td>41.14</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>113.79</td>
<td>37.93</td>
<td>3.21</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>8.57</td>
<td>2.86</td>
<td>0.35</td>
</tr>
<tr>
<td>Pan</td>
<td>&lt;75</td>
<td>0.72</td>
<td>0.24</td>
<td>0.11</td>
</tr>
</tbody>
</table>

\textsuperscript{187} Well-graded sand is important for shrinkage control. Well-graded implies a uniform variation in size from very small to the maximum size in the sand being used. This is important since smaller grains fill the voids between the somewhat larger grains, and the combinations of smaller grains fill the voids between the larger grains. Ideally, this results in a mixture in which the paste need only coat the grain, and not be counted on to also fill voids. The grains will not shrink, but the paste may. The more tightly packed, the less paste is needed, and thus the less shrinkage is likely to occur (Nels Roselund. “Sand Selection for Grout.” Email to Kelly Wong. January 13, 2006).

Graph 4.1. Particle Size Distribution for Yellow Bar Sand

4.2.3 Formulations

According to previous research, grout formulations with a binder to aggregate ratio of 1:3 produced successful experimental results and was selected as the control formulation (A) to be tested in the current research.\textsuperscript{189,190} The addition of crushed bricks in two varying proportions, one formulation (B) with equivalent brick dust to lime (1 : 1 ratio) and the second (C) with half the volume of brick dust to lime (0.5 : 1 ratio) will also be tested for its effect on set, strength, and shrinkage. Formulation C is based on a similar grout formulation specified and used for the stabilization of the Early Phrygian Gateway. For

all grout formulations, the volume of liquid required to reach the desired consistency was
determined and the volume remained constant for each batch of a given formulation.

Grout formulations tested in the current research is shown in Table 4.3.

### Table 4.3. Grout formulations tested in Current Research

<table>
<thead>
<tr>
<th>Sample Designation</th>
<th>Proportions (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydrated Hydraulic Lime (Chaux Blanche)</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
</tr>
</tbody>
</table>
4.3 Sample Preparation

4.3.1 Grout Samples

The grout samples used for the laboratory testing program were prepared according to the specifications outlined in ASTM C192/C 192M-00 “Standard Practice for Making and Curing Concrete Specimens in the Laboratory,” except in this case, the specimens were not moist cured. Moist curing, where free water is maintained on the sample surface from days 7 to 28 of curing for the 28-day tests, was not conducted since lime based formulations harden better in drier environments and a lower humidity simulates more accurately the environment found at Gordion, Turkey.

2.4.2 Grout Mixing

Per formulation, the dry components were initially sieved before mixing thoroughly in order to break up lumps and remove any foreign materials (Fig. 4.1). Dry ingredients included the

Figure 4.1. Sieve shaker used for sieving the sand (Wong 2006).
hydrated hydraulic lime, sand, and brick dust. The fine particle-sized lime first passed through a No. 20 sieve (passing particles < 850μm) (Fig. 4.2) to reduce clumps during mixing according to ASTM C141 “Standard Specification for Hydraulic Hydrated Lime for Structural Purposes,” and mixed with the sand (Fig. 4.3) that was previously dried and sieved to pass through a No. 18 sieve (passing particles < 1000μm) as specified in the project specifications for the grout used at the Citadel Gate. Where the formulation required, the brick dust previously sieved in Puerto Rico to pass through a No. 200 sieve (passing particles <75μm) was mixed with the lime and sand mix. The temperature of

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the air in the vicinity of the dry materials and mixing was maintained between 68 and 81.5°F (20 and 27.5 °C).

Subsequently, the dry components were mixed with water. The water to binder ratio used in the grout formulations was determined by the minimum amount of water required to pass the “Marsh Flow Cone” test according to ASTM C939-97 “Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method).”

Water is gradually introduced into the dry mixture in order to establish the suitable water to binder ratio. Approximately 1 part water to 3 parts dry grout mixture was used for all three formulations. De-ionized water at a consistent temperature at 73.4 °F (23 °C), as specified by ASTM C141-97, “Standard
Specification for Hydraulic Hydrated Lime for Structural Purposes,” was used for this procedure. The ingredients were mixed in an 11.8 liter seamless stainless steel pail with tapered sides using a hand-held cored Milwaukee 3/8” electric drill of variable speed control between 0-1200 rpm. A 48 cm long vertical stainless steel paint mixer was attached to the chuck of the 7.0 AMP cored drill. The agitator end of this mixing attachment is similar to the solid and butterfly agitators on the Hamilton Beach Commercial Model 936 Drink Mixer192. The benefit of using this attachment is its ability to move around the entire steel pail creating a vortex to ensure an even mixing and distribution of the grout (Fig. 4.6). Standard mixing times and speeds ensured consistency and quality control among the three grout formulations.

The amount of dry mixture used per batch mixed ranged in volume between 4,800 ml and 6,000 ml (see Appendix B. Experimental Program Data for mixing details per formulation). One batch per grout formulation was enough to fill all the molds necessary for the laboratory testing. Due to the large quantity of dry ingredients used per batch, the

192 The Hamilton Beach Commercial Model 936 Drink Mixer has been consistently used in past University of Pennsylvania Historic Preservation theses laboratory testing for grout mixtures of finer particle sizes required to pass through a small #16 gauge stainless steel cannula (Claudia Cancino. Assessment of Grouting Methods for Cracks and Large Scale-Detachment Repair at Casa Grande Ruins National Monument. Masters Thesis. University of Pennsylvania, Graduate Program in Historic Preservation. 2001. 133) used for small scale grout applications such as the reattachment of plaster finishes. Other mixing devices used in the past include an ordinary kitchen blender which resulted in poor quality grout. In comparison to the Hamilton Beach mixer, grouts mixed using the kitchen blender produced less thixotropic grouts and tended to bleed more readily, indicating the segregation of components and the inability to thoroughly disperse the water around the fine dry ingredients.
grout was first mixed by hand to thoroughly introduce the initial amount of water for about two minutes (Fig.4.5).

The grout mixture was then mixed using the corded drill for approximately five minutes on the drill’s low setting at 800 rpm. The sides of the pail were scraped down with a rubber spatula and the setting was adjusted to medium at 1000 rpm where the grout was mixed for another five minutes. After mixing at medium speed with the addition of more water, greater workability was achieved in all three grout mixtures. Again, the pail’s sides were scraped down and the setting was adjusted to high at 1200 rpm where the
grout was mixed for between 16 to 24 minutes, depending on the amount of dry mixture used. Total mixing time for each of the three grout formulations varied from 26 to 34 minutes. Long time mixing is considered one procedure that contributes to optimal mixing, producing good fluidity and increased stability in grouts.\(^{193}\)

High speed mixing is critical in achieving a high quality grout. Good workability ensures proper injectibility through the specified apparatus, with enough water retention to counter suction from porous building materials and allow adequate hydration of the hydraulic lime. Workability also provides the grout compositional stability through its set and cure time. High velocity mixing breaks down the clumps of the dry ingredients, allowing individual grains to be thoroughly dispersed and placed in suspension while breaking down the hydraulic lime particles and exposing new areas to water and activating the first phase of hydration.\(^{194}\)

Though a true centrifuge was not obtained during the mixing as the mixer was continually moved around the vortex drum, it is assumed that the high speed of the mixture was sufficient to fully integrate all particles, dispersing them within the total mixing time applied. Houlsby describes this mixing procedure for making grout as


adequate and comparable to that of a high-speed, high-shear mixer if operating at 2000 rpm, however notes that this method still produces a lower quality grout.

In the field, a grout mixer is used for producing large batches for *in situ* application of injection grouting. Grout mixers used in past restoration efforts have included high-turbulence mixers, an UltraSonic mixer (US-mixer), and other set ups depending on the scale of the project. The second, used in one case study for mixing grout consisting of lime, pozzolan, cement, silica fume, and superplasticizer enables an ultra-sonic dispersion at 28 kHz and mechanical stirring at 300 rpm. The advantages of using an ultra-sonic mixer are its ability to reduce water to achieve penetrability while allowing better dispersion and wetting of the particles. However, the disadvantages of using the UltraSonic mixer include the increased probability of micro-cracking caused by the dispersion process and its current unavailability in the commercial market.  

Once the grout mixture appears to have a consistency allowable to pass the fluidity test using the Flow cone method, the mixing time is recorded.

**2.4.3 Molding, Curing, and De-Molding**

After the grout mixture passes the fluidity test using the Flow cone method, it is poured into molds specific to each test. A total of 54 molds were filled, 18 for each of the three

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grout formulations. See Table 4.4 for detailed specifications of each mold type as designated by ASTM C192/C 192M-00 “Standard Practice for Making and Curing Concrete Specimens in the Laboratory.”

### Table 4.4. Laboratory Specimens Schedule (For Three Formulations)

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Shape</th>
<th>Size</th>
<th>Amount per Formulation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHYSICAL – CHEMICAL PROPERTIES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sieve Analysis</td>
<td>ASTM C136</td>
<td>Angular - Subangular</td>
<td>0-1mm</td>
<td>300 g</td>
<td>300 g</td>
</tr>
<tr>
<td>Material Composition</td>
<td>Physical Characteristics</td>
<td>Angular - Subangular</td>
<td>0-1mm</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>WORKABILITY TESTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluidity</td>
<td>ASTM C939</td>
<td>---</td>
<td>---</td>
<td>1725 ± 5 ml</td>
<td>5175 ± 15 ml</td>
</tr>
<tr>
<td>Setting Time</td>
<td>ASTM C191*</td>
<td>Truncated Cone</td>
<td>60mm dia. Top 70mm dia. Base 40mm height</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>Visual Analysis</td>
<td>Unglazed Saucer</td>
<td>3.25” dia. Top 2.5” dia. Base 1” height</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td><strong>STRENGTH TESTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Splitting Tensile Strength</td>
<td>ASTM C496</td>
<td>Plastic Cylinder</td>
<td>2” dia. x 4” height</td>
<td>(3) 28 days (3) 60 days</td>
<td>18</td>
</tr>
<tr>
<td><strong>TOTAL Samples</strong></td>
<td></td>
<td></td>
<td></td>
<td>9 cones, 9 saucers, 18 plastic cylinders</td>
<td></td>
</tr>
</tbody>
</table>

AN ASTERISK (*) INDICATES THAT THE LISTED STANDARD WAS USED AS A GUIDE
4.3.3.1 Molding

All molds were coated with a releasing agent to enable easy removal of samples during de-molding after seven days (Fig. 4.7). The wood molds used for producing the 2” cubed specimens in preparation for future testing of salt crystallization (and not used in this thesis) were brushed with mineral oil. The plastic molds including the Vicat truncated molds for set time testing and cylindrical plastic molds used for splitting tensile strength testing were all coated with a thin layer of petroleum jelly. While the Vicat molds were positioned on uniform acrylic squares, the cylindrical molds were placed on an absorptive drywall surface. All plastic molds were sealed at the bottom with a thin bead of plumber’s putty to prevent leakage. The unglazed terra cotta saucers used for the visual shrinkage test were pre-soaked in de-ionized water 48 hours prior to filling.

Figure 4.7. Molds prepared for the laboratory grout specimens (Wong 2006).
Small plastic beakers were filled with the grout mixture obtained from the stainless steel pail as it was being continuously mixed with the electric drill. Once the plastic beakers were filled with the grout mixture, they were continuously hand stirred with a glass rod before and during pouring into the molds (Fig. 4.8). Each mold was filled with the grout mixture until overflowing. After all molds were filled per formulation, glass rods were used to puddle samples to reduce air bubbles within the mold which may have formed during the pour (Fig. 4.9). After approximately 15 hours, the tops of the molds were carefully scraped off using a wide metal putty knife (Fig. 4.10).
Sample Pouring and Molding

**Figure 4.8** (top left) Constantly stirring mixture while pouring samples into molds.

**Figure 4.9** (top right) Puddling samples with a glass rod to prevent air bubble which may have formed during pouring.

**Figure 4.10** (bottom) Samples after excess grout was scraped off.
2.4.3.2 Curing and De-Molding

The grout specimens were cured for a minimum of 28 days. The specimens were left to dry in an open laboratory environment for the first seven days of curing. Temperature in the laboratory fluctuated between 16-21 °C (60.8-69.8 °F) and relative humidity between 31-57%. At day eight, the specimens were de-molded (Fig. 4.11) and placed into a high humidity “moist closet.” The moist closet consisted of a baker’s rack, a plastic rack cover, and trays filled with de-ionized water within the chamber (Fig. 4.12). The aimed relative humidity level of approximately 90% was regulated before insertion of the specimens. A dial hygrometer was placed in the middle rack for daily monitoring of the relative humidity and temperature of the chamber during the cure. The moist closet temperature ranged between 16-24 °C (60.8-75.2 °F) and relative humidity between 75-
99%. Previous theses have also followed the curing procedure specified in the German standard DIN 18-555. The specimens which are covered with a layer of liquid water are placed on wire racks to expose all surfaces to air, allowing for quick absorption of CO₂. Though the presence of moisture facilitates carbonation reaction of the lime and crystallization of calcite crystals, excess moisture under these conditions could also lengthen the reaction time. Due to the relatively quick set and stability of the three grout formulations, the samples produced for this thesis was de-molded after only 7 days.

4.4 Physical Tests

The following tested properties were determined to be critical in the initial evaluation of the performance of grouts used in the conservation of historic structures and applicability to the stabilization of the Early Phrygian Gateway at Gordion:

- Viscosity
- Setting time
- Drying Shrinkage
- Resistance to shear forces (splitting tensile strength)

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The first three examine the workability of each grout formulation whereas the last test assesses the strength of the grouts in terms of structural integrity.

4.4.1 Workability

Grout design involves learning about the physical-chemical properties of the mixtures including the “rheological” property of a grout mixture. Rheology is the study of the deformation and flow of matter. Rheological descriptions usually refer to the property of viscosity.\(^{197}\) Process parameters of injection grouting are determined by injectibility and mechanical characteristics of the grout mixture, properties of the existing masonry, appropriate data about grouts, and interaction between masonry and grout.\(^{198}\)

Workability tests assess the properties of grouts in their plastic state before curing and allow for better understanding of the rheological character of the grout and its suitability for \textit{in situ} application. Workability tests conducted for this research include fluidity, setting time, and drying shrinkage.

\(^{197}\) Viscosity is defined as the internal fluid resistance of a substance which makes it resist a tendency to flow (American Society of Civil Engineers. “ASCE Grouting Committee (Preliminary glossary of terms relating to grouting).” In \textit{Journal of the Geotechnical Engineering Division} (1980): 814.)

4.4.1.1 Viscosity

- ASTM C939-97 “Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)”

This test procedure measures the time of efflux of a specified volume of fluid hydraulic cement through a standard flow cone with a standard diameter outlet and is intended for use with neat and fine-aggregate grouts with aggregate passing through a #8 U.S. standard sieve. Other fluid grouts may also be tested for viscosity in this manner. The maximum allowable time of efflux for this test is 35 seconds. This test is also performed to maintain a quantifiable rate of flow for each of the three grout formulations.

The long flow cone has an 11 inch tall high density funnel shaped polyethylene body with a 7 inch (177.8 mm) diameter opening at the top and a ¾ inch (19.05 mm) stainless steel discharge tube opening at the bottom (Fig. 4.13). The cone is mounted on a ring stand and calibrated. Calibration consisted of leveling the top of the cone and adjusting the bottom of the point gauge to indicate the level of $1725 \pm 5$ ml of volume. A receiving container is placed below the discharge orifice in order to contain the fluid passing through the flow cone during the test.

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The standard requires a preliminary water test before introducing the grout mixture for testing. With a palm at the bottom of the discharge opening, de-ionized water is poured into the flow cone until the level reaches the bottom of the point gauge. If the water drains from the cone within $8.0 \pm 2$ seconds, then the grout flow test can proceed. If the water test is not performed within one minute of the grout flow test, the inside of the flow cone should be moistened with water prior to the introduction of the grout mixture. Since the test is a multi-stepped procedure and the grout is required to be continuously mixed simultaneous to the water flow test, a total of three people performed this operation. While one person continues mixing the grout, the other two perform the
water flow test. Once the water test concludes, mixing of the grout ceases and the pail is continuously stirred by hand with a rubber spatula until it is poured into the flow cone. While the first person has their palm at the bottom of the discharge opening, the second continuously stirs and pours the grout mixture into the flow cone until it reaches the bottom of the point gauge (Fig. 4.14). The third person times the flow test.

The stopwatch is started at the time the palm is removed from the discharge opening and the grout mixture is allowed to flow through the cone. The watch is stopped at the first break of continuous grout flow while looking into it from above and noting the first light visible through the opening. The standard requires a minimum of two samples per formulation with efflux times within 1.8 seconds of each other in order to pass the test. The results are then averaged as the flow value.

4.4.1.2 Setting Time


Set time is critical in grouts used for the stabilization of historic structures. Also known as the stiffening rate, setting time allows for the measurement of the time for a grout formulation to solidify in order to determine whether a formulation is adequate for injection into voids requiring specific curing requirements. For cementitious and lime-
based grouts that undergo physical and chemical change as a result of water loss and chemical reaction with atmospheric CO₂, it is possible to evaluate and compare formulations in terms of their set time using the Vicat Needle method. It was critical to formulate a grout that has a fast initial set, but slow final set. A fast initial set for grout has the advantage of first attaining a stable physical structure with enough shear strength to resist settlement of the suspension and displacement of the loose fragments. A slow final set enables proper curing as well as the formation of a stable bond between the grout and the adjacent materials to which it adheres. Initial set times of the three grout formulations in this thesis research were determined using a Vicat needle following ASTM C191-77 “Standard Test for Time and Setting of Hydraulic Cement by Vicat Needle.”

The Vicat test method provides an accurate measurement of initial and final set times for grout and allows for the comparison of different formulations. Due to the liquid nature of grout, the sample molding procedure was modified in order to perform this test. The standard specifies the initial set time as the time when a penetration of 25mm is obtained and final setting as the point when the needle does not sink visibly into the mold.
The Vicat molds are truncated cones with a top diameter of 60mm, a bottom diameter of 70mm, and a height of 40mm. The mold is coated with a thin coat of petroleum jelly as a releasing agent at its interior and positioned on a square sheet of acrylic. A bead of plumber’s putty is sealed at the bottom of the mold to prevent any grout leakage. Rather than rolling the mortar “into a ball…and toss six times from one hand to the other” as specified by the standard, the grout mixture is carefully poured into the mold until it overflows (Fig. 4.15). Molds are then puddle with glass rods to reduce air bubbles which may form during the pour. Excess grout is slowly scraped off the top of the molds with a wide metal putty knife a few hours after pouring.
Test specimens are immediately placed in a moist closet with high relative humidity (+ 50%) and left in this controlled environment except when determining depths of penetration. During readings, the molds are placed under the penetrometer (Fig. 4.16). The test is conducted by lowering the tip of the 1mm diameter stainless steel “Vicat” needle until it rests on the sample, adjusting the depth indicator to zero, and tightening the set screw. Upon loosening the set screw, the needles lowers quickly by gravity, enabling the needle to penetrate for the indicated 30 seconds before a reading is taken. The standard does not allow for penetration readings to be taken any closer than ¼ inch from any previous penetration or closer than 3/8 inch from the rim of the mold.
4.4.1.3 Drying Shrinkage

- Visual Assessment

Drying shrinkage of the grout formulations was visually assessed. Acting as an adhesive and void filler in masonry structures, it is necessary for grout to maintain dimensional stability in order to prevent structural failure attributed to a variety of elements such as poor quality materials, improper mixing, and curing procedures. The drying shrinkage test evaluates the level of acceptable and unacceptable shrinkage for a given grout formulation. Grout samples were also weighed before and after curing in efforts to quantify shrinkage as a function of total weight loss caused by water loss.

Segregation is common in grouts. Solid particles tend to separate and settle into levels depending on their size. Binders such as the hydrated hydraulic lime which are much finer than the coarse sand filler are likely to rise to the surface, leaving behind unbound binder, and allowing larger particles to settle at the bottom of the mixture. This is the reason why high speed mixing is critical for producing well dispersed grout with a homogeneous matrix. Bleeding may also give rise to laitance and produce a layer of weak, non durable material containing dilute calcium carbonate and fines from the aggregate, laitance. Bleeding and rapid evaporation of surface water will leave voids and
will often result in some degree of setting shrinkage.\textsuperscript{200} The laitance layer is highly permeable and is a source of water leakage in hydraulic structures and is particularly vulnerable to freeze-thaw deterioration. Segregation of the grout samples are examined by breaking them in half and examining the grout in cross-section.

For each formulation, the grout was poured directly into three pre-weighed unglazed terra cotta saucers previously soaked in de-ionized water for 48 hours. The terra cotta saucers are 4” in diameter (interior opening) and \(\frac{3}{4}\)” in height. The saucers were left out to cure in the laboratory for the remainder of the testing. After the excess grout is scraped off the tops with a metal putty knife once it gains sufficient stiffness (approximately 15 hours) it is then weighed. At 14 days, the weight of the saucer and sample are weighed and any deformation or shrinkage observed

in the grout is recorded (Fig. 4.17). After one month, visual assessment is again
performed in their semi-cured state. Volumetric percent shrinkage can be measured after
28 days by calculating the difference in specific gravity between grouts in their liquid and
solid states. Though ICCROM states that volume shrinkage should be less than 4%, this
numerical value may not be applicable at such a large scale operation as the Citadel
Gate and would actually depend on the size of the voids within the existing wall system.
Volumetric percent shrinkage was not conducted since no shrinkage was noted during the
visual assessment.

4.4.2 Strength

The strength of the grout depends on its compatibility and ability to bond well with the
existing components of the masonry, as well as on the properties of the grout’s raw
materials. Splitting tensile strength was selected as the best measure of strength for this
application as the existing masonry wall of the Early Phrygian Gate to evaluate the stress
and shear forces of the structure under seismic activity. The stress caused by seismic
activity and possible settlement of the structure are the focus of the splitting tensile
strength. Since the monument stands isolated from any other structure on site, is roofless,
and does not support any direct load above, the compression test was not performed for
the current research. Though bond-shear strength is critical for stabilizing the Gateway,
it was not conducted because limestone samples were not available from the site, making

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it difficult to characterize and build assemblies of their different adherents for testing.

Improving the mechanical behavior of a structure requires the design of a grout with good injectibility and bonding properties. Good bonding limits the intrusion of detrimental agents and subsequent chemical reactions (e.g. water, sulphates, salts) and resists against deterioration due to environmental factors. Characteristics of good bonding with the existing materials include relatively low shrinkage, minimal heat of hydration, and setting in dry as well as wet environments.\textsuperscript{202} Bond-shear strength tests are critical and should be conducted in the future experimental program of Phase II for the Citadel Gate.

4.4.2.1 Splitting Tensile Strength

- ASTM C496-96 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens”

To resist differential movement caused by settlement of the masonry Gate structure and periodic seismic activity, the grout must have sufficient shear strength and act as an intermediary bonding agent between the rubble masonry core and the ashlar limestone facing. The grout must also at the same time possess a low enough strength to fail under extreme loads without damaging the historic fabric. Though it is known from past research that compressive strengths of lime-based mixtures are lower than ordinary cementitious mixtures, the intent of the splitting tensile strength for this laboratory testing

program is to evaluate the strengths influenced by the proportion of crushed bricks in the grout formulations B and C. Pozzolanic reaction is expected to further increase the bond tensile strength after 60 days\textsuperscript{203} as it continues to cure. To assess the shear resistance of the three grout formulations, the samples were tested using ASTM C496-96 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.”

Although this standard is intended for use with concrete specimens, the hydraulic lime grout formulations produced for this thesis research were tested according to the specifications. Tensile strength is defined as the maximum pulling or ductile stress that a material can be subjected to without breakage.\textsuperscript{204} Splitting tensile strength is used to evaluate the shear resistance provided by concrete in reinforced lightweight aggregate concrete members. Additionally, it is simpler to determine the splitting tensile strength rather than direct tensile strength in order to evaluate the shear stresses imposed on a material.

This test determines the splitting tensile strength of cylindrical specimens by the application of a diametral\textsuperscript{205} compressive force along the length of the cylinder at a constant rate until failure. Tensile stresses are induced along the plane where the load is applied.


\textsuperscript{204} Getty Art & Architecture Thesaurus Online website: www.getty.edu/research/conducting_research/vocabularies/aat/

\textsuperscript{205} Diametral: of or pertaining to the diameter. (Dictionary.com: www.dictionary.net)
being applied while relatively high compressive stresses are found in the area immediately around the applied load. Since the areas of load application are in a state of triaxial\textsuperscript{206} compression rather than uniaxial compressive strength, tensile failure occurs instead of compressive failure. Triaxial compression allows the specimens to withstand a much higher compressive stress than that indicated by uniaxial compressive strength test results.

Cylindrical molds used for the splitting tensile strength test are 2 inches in diameter and 4 inches in length, a diameter equal to half the sample’s length (Fig. 4.18). Where the cylinders have been pre-cut lengthwise to facilitate easy sample removal after curing, electric tape is adhered along the seam to avoid leaking of the grout mixture. After being lightly coated with a thin layer of petroleum jelly as the releasing agent, the molds are placed upright on the absorptive surface of drywall and sealed at their bases with a thin bead of plumber’s putty to prevent grout leakage. The grout is poured directly into the cylindrical molds and subsequently puddled with a glass rod to eliminate air bubbles which may form during the pour. Superfluous grout is scraped off with a wide metal

\textsuperscript{206} Triaxial - refers to cable with three concentrically arranged conductors. (www.matel.com.mx/catalog/glossaryt.htm)
Figure 4.18. Cylindrical grout specimens for the splitting tensile strength test (Wong 2006).

putty knife when it has a chance to adequately stiffen, after approximately 15 hours. The samples are then left to cure according to the procedures detailed in Section 2.4.3. (Molding, De-molding, and Curing) according to ASTM C192.

The splitting tensile strength test was conducted at the Laboratory for Research on the Structure of Matter (LRSM) at the University of Pennsylvania under the supervision of
Dr. Alex Radin, the Facilities Manager at the Department of Materials Science and Engineering. The test used an Instron 4206 Static Testing Machine with an electro-mechanical system and a universal type load that can be applied with a constant but adjustable rate of cross head movement (Fig. 4.19).

Figure 4.19. Instron 4206 Static Testing Machine used for the splitting tensile strength test (Wong 2006).
To conduct the test, the sample ends are first drawn with perpendicular diametral lines, both measured to the nearest 0.01 inches and averaged, $D$. The cylindrical grout specimen is then positioned with its axis horizontal between the top and bottom platens of the testing machine, wedged and balanced on the lower platen with two thin plywood bearing strips measuring approximately 1/8” thick x 7/8” wide x 4½” long. The bearing strips ensure that the load is uniformly applied along the length of the cylinder. Force is applied to the specimen from above at a constant load rate of 0.02 inch per minute until failure. Failure is considered the maximum applied load of force required to fracture the specimen, $P$. The splitting tensile strength of a sample is obtained by the maximum load sustained by the sample divided by appropriate geometrical factors, calculated using the following formula:

$$T = \frac{2P}{\pi LD}$$

where, $T$ = splitting tensile strength (psi)

$P$ = maximum applied load indicated by the testing machine (lbf)

$L$ = length (in)

$D$ = diameter (in)
4.5 Future Testing

As a result of the insufficient information of site parameters and lack of appropriate laboratory equipment, specific tests were not conducted in Phase I of this Laboratory Testing Program. See Section 7.1.2 Future Testing for further discussion of future recommended testing and schedule.
5.0 RESULTS & DISCUSSION

Results for the laboratory tests outlined in the previous chapter are reported and discussed in the following section (see Appendix B for all test data). Of the three grout formulations, Formulation B samples produced the promising results for the majority of the tests.207

Table 5.1. Grout Formulations tested in Current Research

<table>
<thead>
<tr>
<th>Sample Designation</th>
<th>Proportions (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydrated Hydraulic Lime (Chaux Blanche)</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
</tr>
</tbody>
</table>

5.1 Grout Mixing

Although grout mixing is not one of the workability tests, observations made during the procedure are presented here. Three formulas combining various ratios by volume of binder (Lafarge hydrated hydraulic lime), filler (quartz sand), pozzolanic additive (brick dust), and water were mixed according to laboratory preparation standards detailed in

207 This mix ratio of 1 part lime : 3 parts sand : 1 part brick dust (by volume) produced the best results for the setting time and splitting tensile strength tests and was also recommended by the Smeaton Project (Jeanne Marie Teutonico et al. “The Smeaton Project: Factors Affecting the Properties of Lime-Based Mortars.” APT Bulletin 25 (1994) nos. 3-4: 44).
Section 2.4.2  Grout Mixing. A general observation worth noting of the grout mixing procedure is the improved workability of a lime-based grout as a result of longer hand-mixing time.

5.1.1 Discussion

After the dry components were mixed, de-ionized water was gradually added to the mixture throughout the mixing. The water to binder ratio used in the grout formulations was determined by the minimum amount of water required to pass the “Marsh Flow Cone” test. Approximately 1 part water to 3 parts dry mixture (by volume) was used for all three formulations (See Appendix B for details).

All three formulations were first mixed by hand using a rubber spatula followed by a hand-held corded electric drill with variable speed control between 0-1200 rpm until the viscosity appeared sufficient to pass the fluidity test. Since the viscosity was judged based on the appearance and feel of the grout using a trowel, formulations A and B required the addition of more water after their first trial before it passed the “Marsh Flow Cone” test.

Each formulation was mixed in an 11.8 liter seamless stainless steel pail which was large enough to accommodate the calculated amount of grout needed for the prepared sample molds used per formulation.
Three samples per formulation were prepared for each laboratory test that required sample molds and curing. Although four tests were conducted in this laboratory testing program, samples were also prepared for an additional test, Salt Crystallization, to be conducted at a future date (at 180 days – October 16, 2006). Of the five tests, only four required molds: Setting Time, Shrinkage, Splitting Tensile Strength, and Salt Crystallization. The grout used for the fluidity test was poured into the molds for the other three tests. Two sets of samples were produced for the Splitting Tensile Strength and Salt Crystallization tests in order to test at 28-day cure and a future cure (at 180 days). Thus, 18 samples were created for each formulation: (3) Setting Time, (3) Shrinkage, (6) Splitting Tensile Strength, and (6) Salt Crystallization; a total of 54 samples produced in February 2006.

5.1.1.1 Formula A

Formulation A consists of a dry mixture of 1 part hydrated hydraulic lime and 3 parts sand. A total of 1,640 ml (volume) de-ionized water was mixed with 4,800 ml (volume) of the dry mixture, a water to dry part ratio of 1:3.

Samples for Formulation A were produced on February 18, 2006. The mixture was first hand-mixed for 1 minute using a rubber spatula with the gradual introduction of water (720 ml). The corded drill was used to blend the grout at the low setting for 3 minutes (addition of 280 ml water), at medium for approximately 4 ½ minutes (addition of 350
ml water), and at high for a longer 15 ½ minutes (addition of 150 ml water) to break up any clumps and to ensure a good fluidity.

After 9 minutes, at high speed and when 1,350 ml of water (28% of mixture) had already been introduced, workability increased considerably. Formulation A was first mixed for a total of 24 minutes before conducting the first fluidity test. However, after this mixture did not pass the “Marsh Flow Cone” test, the grout was mixed for another 6 minutes and 43 seconds until it was re-tested and passed the test. Formulation A was mixed for a total of 30 minutes and 44 seconds.

A grey discoloration was found within the liquid mixture early on during the electric drill mixing which may have been the product mixing within the stainless steel bucket (Fig. 5.1). The discoloration was more noticeable in this

Figure 5.1. Grey discoloration present in the Formulation A grout mixture during the mechanical mixing procedure (Wong 2006).
formulation since it was a fairly light color as opposed to the other two formulations with brick dust whose rosy tint may have masked the grey. As a consequence of adding too much water at once, air bubbles formed in the mixture during the mechanical drill mixing. Additionally, even after mixing at the low setting on the corded drill, Formulation A was still relatively clumpy and difficult to blend. This may be the result of a combination of not introducing enough water initially during the hand-mixing or the quantity of time (1 minute) mixed before introducing the corded drill.

5.1.1.2 Formula B

Formulation B is composed of a dry mixture of 1 part hydrated hydraulic lime, 3 parts sand, and 1 part brick dust. A total of 2,400 ml (volume) de-ionized water was mixed with 6,000 ml (volume) of the dry mixture, a water to dry part ratio of 1:3.

Samples for Formulation B were produced on February 19, 2006. The mixture was first hand-mixed for 2 minutes using a rubber spatula with the gradual introduction of water (1,000 ml). As a result of the difficulty found in the mixing of Formulation A, it was determined to use more time in hand-mixing. This hoped to thoroughly incorporate the water into the dry mixture. The corded drill was then used to blend the grout at the low setting for 4 minutes (addition of 475 ml water), at medium for approximately 5½ minutes (addition of 175 ml water), and at high for another 15 minutes (addition of 150 ml water) to break up any clumps and to ensure a good fluidity.
Workability improved after mixing for 19 ½ minutes when 1,730 ml of water (29% of mixture) was introduced. Formulation B was mixed for a total of 26 minutes and 45 seconds before conducting the first fluidity test, which did not pass the “Marsh Flow Cone” test. The grout was mixed for another 8 minutes and 52 seconds with an additional 250 ml water until it was tested for the second time and passed. A total mixing time of 35 minutes and 37 seconds with a total of 2,050 ml of water was used for Formulation B.

The mixture for Formulation B was not as clumpy as Formulation A when the electric drill was introduced (Fig. 5.2). This may be attributed to the longer hand-mixing time.
Additionally, only a small amount of aeration occurred during the mixing. The grey discoloration was not observed in Formulation B.

5.1.1.3 Formula C

Formulation C consists of a dry mixture of 1 part hydrated hydraulic lime, 3 parts sand, and ½ part brick dust. A total of 2,160 ml (volume) de-ionized water was mixed with 5,400 ml (volume) of the dry mixture, a water to dry part ratio of 1:3.

Samples for Formulation C were produced on February 18, 2006. The mixture was first hand-mixed for almost 4 minutes using a rubber spatula with the gradual introduction of 1,360 ml of water. With a cored drill, the grout was first blended at the low setting for 1 minute without addition of any water, then at medium for approximately 3 ¾ minutes (addition of 240 ml water), and

Figure 5.3. Presence of air bubbles during mixing procedure of Formulation C (Wong 2006).
finally at high for 15 minutes (addition of 250 ml water).

Workability of the Formulation C improved around 9 minutes when mixing at medium speed after 1,600 ml of water had been added. A large amount of aeration (Fig. 5.3) observed during the mixing of this formulation, especially when using the electric drill. The grey discoloration apparent in Formulation A was also found in Formulation C, albeit slightly. Many air bubbles appeared during the mixing, more than Formulation B. After a total mixing time of 26 minutes and 15 seconds, the fluidity test was conducted using this grout mixture and passed the first time around.

**5.2 Workability Tests**

The workability tests carried out using the three grout formulations showed satisfactory results and allowed to make some considerations on the injection techniques. Laboratory tests have their limits since only small quantities are evaluated and a laboratory environment does not exactly represent the actual environment. However, use of standards to assess a specified composition such as grout is critical in understanding the performance of a mixture composed of different materials. Moreover, use of standards allows for comparison of data and thus has the potential to assist developing broader based performance standards for specific and general situations.
5.2.1 Viscosity

5.2.1.1 Results

All three grout formulations passed the fluidity test. However, Formulations A and B both required re-testing after their first trials. During their first trials, the entire volume of grout did not pass through the orifice and required additional water and consequently, more mixing time. See Table 5.2 for the Flow Cone test results.

Table 5.2. Flow Cone Test Results

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (volume)</th>
<th>Trial #</th>
<th>Marsh Flow Cone 1,750 ml Efflux (seconds)</th>
<th>Average Efflux (seconds)</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Water @ 20ºC ÷ 3ºC</td>
<td>1</td>
<td>2.43</td>
<td>2.43</td>
<td>Yes</td>
</tr>
<tr>
<td>A</td>
<td>1 HHL : 3 S</td>
<td>1</td>
<td>-</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8.84</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>9.44</td>
<td>9.14</td>
<td>Yes</td>
</tr>
<tr>
<td>B</td>
<td>1 HHL : 3 S : 1 B</td>
<td>1</td>
<td>-</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8.28</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>8.38</td>
<td>8.33</td>
<td>Yes</td>
</tr>
<tr>
<td>C</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>1</td>
<td>10.10</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>10.75</td>
<td>10.43</td>
<td>Yes</td>
</tr>
</tbody>
</table>

HHL – Hydrated Hydraulic Lime  S – Quartz Sand  B – Crushed Brick
5.2.1.2 Discussion

The efflux times of all three grout formulations were measured using the Marsh Flow Cone (Fig. 4). Viscosity was measured to maintain consistency and quality of the grout as a reference standard throughout the testing program. ASCE Grouting Committee defines viscosity as “the internal fluid resistance of a substance which makes it resist a tendency to flow.”\textsuperscript{208} ASTM measures viscosity as a rate, in terms of time required, for a known quantity (1,750 ml) of grout to flow through a standardized funnel with a specified diameter outlet (Fig. 5.4). The standard requires a minimum of two samples per formulation with efflux times within 1.8 seconds of each other in order to pass the test. The results are then averaged as the flow value. Moreover, a preliminary water test (within 8.0 $\pm$ 2 seconds) is performed.

\textsuperscript{208} American Society of Civil Engineers. “ASCE Grouting Committee (Preliminary glossary of terms relating to grouting).” In \textit{Journal of the Geotechnical Engineering Division} (1980): 814.

![Figure 5.4](image)

*Figure 5.4.* Formulation B grout mixture flowing through the Marsh Flow Cone (Wong 2006).
before testing of the grout can proceed. Thus, the flow rate is relative to the rate of 
water flowing through the funnel. The maximum allowable time of efflux for using this 
test is 35 seconds. The average efflux times for the three grout formulations ranged 
between 8.33 seconds to 10.43 seconds.

Fluidity of grout is important to allow proper injectibility. If injection cannot be 
properly carried out, the voids for example within the masonry walls at the Citadel Gate 
will not be completely filled with the grout and good adhesion between the limestone 
veneer and rubble core thus cannot be achieved. Grout that is too thick will accumulate 
near the injection point and block the passage of more material that is to follow. Past 
studies have shown that when an injection is blocked, it is impossible to restart the flow 
by increasing pressure whether they are caused by sudden or gradual obstructions.209 
Too thin of a grout will permit components to segregate and the mixture will not cure or 
perform as expected.

5.2.2 Setting Time

5.2.2.1 Results

The Vicat test results showed the direct effect of the type and proportion of binder 
(hydrated hydraulic lime and brick dust) to the filler (sand) on set time. The amount of

209 S. Ignoul et al. “Application of Mineral Grouts for Structural Consolidation of Historical 
370.
brick dust used in the mixtures determined early set of the grout mixtures. Brick dust containing Formulations B and C showed earlier “initial” and “final” set times than Formulation A and the higher proportion of brick dust used in the mixture, the quicker the set. All three formulations showed final set times within 25 hours. See Table 5.3 for the average Setting Time test results.

Table 5.3. Average Setting Time Test Results

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (weight)</th>
<th>Initial Set Time (hours)</th>
<th>Final Set Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 HHL : 3 S</td>
<td>13.5</td>
<td>25.0</td>
</tr>
<tr>
<td>B</td>
<td>1 HHL : 3 S : 1 B</td>
<td>9</td>
<td>15.5</td>
</tr>
<tr>
<td>C</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>11</td>
<td>16.5</td>
</tr>
</tbody>
</table>

HHL – Hydrated Hydraulic Lime  S – Quartz Sand  B – Crushed Brick

5.2.2.2 Discussion

The standard defines initial set time as the time when a penetration of 25 mm is obtained and final setting as the point when the needle does not sink visibly into the mold. Initial set times for the three formulations ranged between 11 mm and 13 ½ mm and final set times between 15 ½ mm and 25 mm. Average setting times show that although Formulations B and C have approximately the same final set times (15.5 hours and 16.5 hours respectively), Formulation B has a more rapid rate of stiffening than C.
Graph 5.1. Average Setting Times

Graph 5.2. Average Setting Times showing Initial and Final Sets

A grout that has a fast initial set has the advantage a stable physical structure (matrix) which can provide sufficient shear strength to resist settlement of any suspended or
displaced fragments within the area of grouting. A slow final set would enable proper curing as well as the formation of a stable bond between the grout and existing fabric to which it needs to adhere. The amount of brick dust added was not found to increase set time proportionally, that is to say doubling the amount of brick dust did not half the set time. The addition of brick dust did increase the initial set time of the unmodified Formulation A by 38% for Formulation B and 34% for Formulation C. This characteristic is attributed to its small particle size (75μm) and low firing temperature of the brick. The low calcination temperature contributes to the pozzolanic reaction with the lime. Acting as a pozzolan, the smaller the particle size, the quicker the set time.\textsuperscript{210} Larger particle size

brick dusts act more as a porous particulate and can assist in carbonation and improved frost resistance.

5.2.3 Shrinkage

5.2.3.1 Results

The shrinkage test showed very little or no visible shrinkage for all three grout formulations (Fig. 5.6). No settling was found either for the three grouts. The only observable change in the samples was slight perimeter cracking or separation from the rims of the unglazed terra cotta saucers in Formulation B samples (Fig. 5.7).

![Figure 5.6](image-url) (Left) Visible Shrinkage Test samples after 30-day cure (Wong 2006).
5.2.3.2 Discussion

Since grouts are used as both void fillers and adhesives, selection of an appropriate formula is critical for maintaining its dimensional stability. Grout shrinkage is influenced by several factors including, the ratio of the constituents (lime, sand, brick dust, and water) used, grain size distribution (grading), water absorption by the binders and aggregates, the reaction between all components, and the surrounding environment including temperature and humidity during cure. The samples were assessed after cured for 14 days (the first 7 days in open laboratory temperatures and the remaining time in the moist closet of high relative humidity). The unglazed terra cotta saucers used, which were pre-soaked for 48 hours before use to contain the grouts can be seen as a similar material as the porous limestone veneer and rubble core at the Early Phrygian Gate structure which is sprayed down and injected with water prior to the injection grouting.

Figure 5.7. Sample B1 showing slight separation at the perimeter (Wong 2006).
Very little or no visible shrinkage of grout samples most likely show that the quantities of water used for the grout formulations were sufficient. Past research has shown that use of higher volumes of water in mixtures increases the likelihood of shrinkage. Of the three grouts, only Formulation B showed slight separation at the perimeter of the unglazed terra cotta saucers (Fig. 5.7). This failure is not easily apparent until close examination of the specimens.

Samples were also weighed before and after 14 day cure in an attempt to quantify shrinkage as a function of total weight loss. Weight loss of the grouts can be attributed to loss of water by evaporation. Overall, Formulations A showed the greatest percentage of weight loss within the time period with a mean of 10.3%, followed by Formulation C with 7.6%, and finally Formulation B with 7.1% (See Table 5.4). It appears that the percentage weight loss may be influenced by the porosity of a grout formulation. The high percentage weight loss for Formulation A could be attributed to the high porosity of the grout mixture, where the aggregate sand makes up for a larger percentage of the formulation matrix (3 parts sand to 1 part HH lime, thus 75% of matrix). Whereas, the brick dust in Formulations B and C acted more as a fine filler in the paste because of its small particle size (75 μm). Complete data and calculations for the percentage weight loss are presented in Appendix B.
Table 5.4. Shrinkage Test Results (by weight) at 14 day cure

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (volume)</th>
<th>% Weight Loss</th>
<th>Mean %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1 HHL : 3 S</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>1 HHL : 3 S</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>1 HHL : 3 S</td>
<td>11.0</td>
<td>10.3</td>
</tr>
<tr>
<td>B1</td>
<td>1 HHL : 3 S : 1 B</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>1 HHL : 3 S : 1 B</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>1 HHL : 3 S : 1 B</td>
<td>8.2</td>
<td>7.1</td>
</tr>
<tr>
<td>C1</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>8.0</td>
<td>7.6</td>
</tr>
</tbody>
</table>

HHL – Hydrated Hydraulic Lime S – Quartz Sand B – Crushed Brick

5.3 Durability Tests

5.3.1 Splitting Tensile Strength

Research indicates that intrinsic mechanical properties need to be checked for meeting required rheological properties such as shrinkage and adhesion including splitting tensile strength.\textsuperscript{211} For grouts, tensile strength and bond-shear strength are more important than compressive strength because once injected into the masonry core, the grout acts as a consolidant to unify the loose components of an assembly. Uniform filling of cracks and voids will allow for the Citadel Gate structure to become a single solid assembly under seismic activity.

Three specimens per formulation were tested for their splitting tensile strength after 28 days of curing. All of the cylindrical grout samples tested in this procedure were subjected to a compressive force applied along their diametric planes (length) between wooden (pine) bearing strips by the Instron 4206 static testing machine (Fig. 5.8). The bearing strips evenly distribute the force applied by the load cell from above along the diametric planes.
Splitting tensile strengths, expressed in psi (pounds per square inch) were calculated to the nearest 5 psi using the following equation:

$$T = \frac{2P}{\pi LD}$$

where, $T$ = splitting tensile strength (psi)

$P$ = maximum applied load indicated by the testing machine (lbf)

$L$ = length (in)

$D$ = diameter (in)

5.3.1.1 Results

Results from the splitting tensile strength test showed the best performance (strongest) by Formulation B, followed by Formulation C, then A where average maximum load capacities were 85.14 psi, 37.73 psi, and 32.73 psi respectively. Results for specimen A3 were lost due to technical error and omitted from the data set. See Table 5.5 for Splitting Tensile Strength Test Results and Data. (See Appendix B for data and detailed calculations).
Table 5.5. Splitting Tensile Strength Test Results (after 28 day cure)

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (weight)</th>
<th>Splitting Tensile Strength (psi)</th>
<th>Average Splitting Tensile Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1 HHL : 3 S</td>
<td>34.83</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>1 HHL : 3 S</td>
<td>30.62</td>
<td>32.73</td>
</tr>
<tr>
<td>A3</td>
<td>1 HHL : 3 S</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>1 HHL : 3 S : 1 B</td>
<td>106.07</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>1 HHL : 3 S : 1 B</td>
<td>64.01</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>1 HHL : 3 S : 1 B</td>
<td>85.35</td>
<td>85.14</td>
</tr>
<tr>
<td>C1</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>35.25</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>35.25</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>1 HHL : 3 S : 0.5 B</td>
<td>42.68</td>
<td>37.73</td>
</tr>
</tbody>
</table>

HHL – Hydrated Hydraulic Lime   S – Quartz Sand   B – Crushed Brick

5.3.1.2 Discussion

Results for the splitting tensile strength test indicate that the ratio of binder to filler influences the grout’s strength; more specifically, the quantity of low-fired brick dust used within a mixture had a direct effect on performance. The higher the proportion of brick dust, the higher the strength. Additionally, higher strength can also be the result of the low calcination temperatures of the bricks as well as the small particle size (75 μm) brick dust used in grout Formulations B and C.

These results of course, only show the early strengths of the grouts after curing for 28 days. Past research has shown that strength specifications for hydraulic limes based on
28 day strengths may substantially underestimate longer term strengths.\textsuperscript{212} For this reason, one extra set of grout samples were produced for future testing, after curing for 180 days.

Much work has been completed to correlate the calcination temperature with the reactivity of calcined clay which undergoes several changes prior to recrystallization at high temperatures. It has been found that the optimum temperature for use as pozzolanas is in the range 700-850°C. However, it has also been found that test samples fired at temperatures as high as 950°C may still yield optimum performance after a prolonged curing period which demonstrates the kiln temperature of the brick dust may be rate dependent.\textsuperscript{213} Thus, influence of calcination temperature is a function of age, curing and fineness which provides the opportunity for pozzolanic reactions to occur. Although no specifications were given with the brick dust used for this testing program, it is presumed that 18\textsuperscript{th} century bricks from Puerto Rico were most likely fired at below 950°C.

Furthermore, results from laboratory and field testing for the Smeaton Project showed the critical effects of brick dust in lime-based mixtures based on three factors: the firing temperatures of the bricks, particle size, and proportions used in a mixture. Lime-sand-


\textsuperscript{213} Ibid. 351-352.
brick dust mixtures using “low fired” brick dust from bricks fired at a temperature at 950°C or lower show increased strength and durability. When a higher proportion of brick dust with smaller particle sizes < 75 μm is used in the mix, this quality is even more pronounced.\textsuperscript{214} Fine particle size brick dust as a pozzolan, when combined with enough water for pozzolanic reactions, can allow engineering of a wide range of strengths.\textsuperscript{215} The trial with a smaller ratio of brick dust (1 part lime to 0.25 part brick dust) in one study performed poorly in comparison to one with a larger ratio of brick dust (1 part lime to 1 part brick dust) and showed considerable surface loss where damage by frost action occurred.\textsuperscript{216}

Slightly quicker set of mixtures using low-fired brick dusts have also been seen to contribute to initial strength.\textsuperscript{217} As a result of early set, the formation of a crystallized matrix for formulations containing brick dust (B and C) may achieve earlier strengths and physical stability early on before formulations without brick dust (A). The small particle size brick dust tends to increase strength by bridging gaps between the larger particle size aggregate to produce a stronger lattice.

Graphs

The following graphs #3, 4, and 5 show splitting tensile strengths of the tested specimens. Each graph shows a comparison of the performance for each of the samples within a formulation under an applied load of 0.02 inch per minute. For Formulations A and C samples, the load is graphed at 1 volt = 100 lbs whereas, Formulation B is graphed at 1 volt = 200 lbs because of its higher load capacity.

![Initial cracks down the center of the cylinder for Formulation A (left), Formulation B (center) and Formulation C (right) samples (Wong 2006).]

During testing, it was observed that when compressive force was applied to the specimens, many of them compressed and displaced considerably before failure or collapse. The lines represented in the graphs are indicative of the characteristic performance of each of the tested grout specimens. The initial curve at the beginning of each sample shows the adjustment of the specimen as it becomes flush with the top and bottom platens of the Instron static machine. Once the adjustment is made, the
performance is represented as a straight line until its first yielding point. This first yielding point, where displacement occurs, is considered the maximum applied load (lbf) used for calculating the splitting tensile strength value. At this point, it was observed that the cylinders typically cracked down the center and separated a little (Fig. 5.9). When this displacement occurs, a continued strength is found within two different points on the specimens – one on each side of the broken cylinder. Thus, this gradual return of strength can be seen in most specimens after its first yielding point. Samples sometimes showed more than one peak (return of strength) after their first yielding point. This displacement shows that the grouts are fairly flexible and could withstand a certain amount of stress before collapse. At the point of total failure, the specimens break apart completely (Fig. 5.10). The stronger specimens (B1, B2, and B3) tended to stay in two pieces whereas, the weaker specimens (A1, A2, C1, C2, and C3) showed vulnerability of breaking into smaller pieces due to physical instability.

For Formulation A samples, A1 and A2, the first yield points are found earlier on along the displacement between 0.02 in and 0.04 in. However, Sample A2 after applied load dissipates and returns twice at two peaks at almost 0.08 in and again at 0.11 (between 0.10 in and 0.12 in) (Graph 5.3). Because of early displacement, the slope of both Samples A1 and A2 appear to be steep. The trend of a steep slope shows a rather weak characteristic in comparison to the other two formulations where the maximum applied load occurs at a small displacement range. A gradual slope to the first yield point tends
to allow for greater displacement and may assist in buying time before complete collapse or failure occurs. Another interesting result found for Sample A1 was the higher load capacity of its secondary peak near 0.09 in of 340 lbf as opposed to its first yield point near 0.02 in of only 240 lbf. Grout samples for Formulation A had the weakest tensile strengths.

Figure 5.10. Sample B3 at total collapse (Wong 2006).
Graph 5.3. Splitting Tensile Strength for Samples A1 and A2

For samples B1, B2, and B3 for Formulations B with the 1 part brick dust, splitting tensile strengths were the highest. In Graph 5.4, the applied load is represented differently at 1 volt = 200 lbs, thus twice the amount than for Formulations A and C. The decision was based on the exponential strength of the samples. Formulation B samples are more consistent in their performance than Formulation A samples. Again, the initial curve at the beginning of the curve shows the adjustments made by the cylinders as they become completely flush to the top and bottom platens of the Instron static machine. The gradual slope and straightness of the line showing the ability to resist the compressed force is indicative of all three samples.
Graph 5.4. Splitting Tensile Strength for Samples B1, B2, and B3

The first yield point, where the maximum load capacity is found all fall near the same displacement position of 0.08 in, regardless of the load capacity value. This may be due to the allowable area of displacement within that given cylindrical specimen before it yields to the applied shear force. This is of critical importance, especially in the case of the Citadel Gate structure which sits within a seismic zone because the displacement caused by earthquake activity can be increased by the use of more brick dust in the grout formulation.
It appears that for samples with higher strength (with a higher load capacity) like Samples B1 and B3, the slope tends to drop off significantly after that point until it reaches failure. However, the weaker the sample (with a lower load capacity) shown an inclination to return again with another larger peak after its first yield point, as in Sample B2. This can also be seen in Samples A1, A2, and C3. Samples for Formulation B showed the highest strengths after 28 day cure.

**Graph 5.5. Splitting Tensile Strength for Samples C1, C2, and C3**

Overall, splitting tensile strengths for Formulation B performed better than Formulations A and C even after averaging the results of the samples tested within a given formulation.
The average splitting tensile strengths (psi) show that Formulation B samples achieved strengths of 62% greater than Formulation A and 56% greater than Formulation C after 28 days cure (see Table 5.6 for average splitting tensile strengths for all three grout formulations).

**Graph 5.6. Average Splitting Tensile Strengths for Formulations A, B, and C**

![Graph showing average splitting tensile strengths](image)

Even at less than half the curing time of 13 days, the sacrificial Formulation B samples (S1, S2, and S3) out-performed the other two Formulations A and C. This shows the rapid initial strength of Formulation B, perhaps as a result of the amount of brick dust in the mixture.
5.4 Sources of Errors

Although the results for testing program tests are extremely helpful in better understanding the performance of the three grout formulations, these values are also highly un-reproducible. These results are not precise and cannot even be considered accurate, but are approximations for all experiments. Precision is the reproducibility of results and accuracy is the correctness of an experimental result. The only type of measurement that can be considered accurate is one involving counting objects, whereas all other measurements contain errors. Imprecision of the data due to systemic errors are caused by instrumental, personal or methodological sources. Although instrumental errors including electronic drift and temperature effects on the detectors were corrected by calibration of electronic devices, personal errors such as judgments made, number bias, and prejudices to improving precision still factors into testing programs.\(^\text{218}\)

Variations in the sample dimensions and composition were also attributed to personal errors during sample preparation. Additionally, methodological errors such as non-ideal chemical or physical behavior of reagents were addressed by using validated methods such as testing standards in order to compare results with other previous research data.

For statistical treatment of errors including standard deviation and confidence limits (90% and 99.9%) for both Setting Time and Splitting Tensile Strength results, see Appendix B. The standard Student’s T-test was not calculated for these data sets

because there were three data sets per laboratory test. The Student’s t-test is used for comparing the means of two treatments, even if they have different number of replicates; thus, compares the actual difference between two means in relation to the variation in the data expressed as the standard deviation of the difference between the means.
6.0 STRUCTURAL ANALYSIS & REPAIR ALTERNATIVE

6.1 Stabilization under Seismic Activity

Grout injection using a hydraulic lime-sand-brick dust mixture has been used to stabilize the Early Phrygian Gate complex since 2001. Although this appears to have been an effective method to consolidate the unreinforced masonry structure, its location within a seismically active zone is a current concern for its stability and longevity. There are several approaches to improving mechanical strength in unreinforced masonry structures, used alone or coupled with injection grouting. Mechanical pinning using fiber-glass rods has been recently introduced to the Citadel Gate structure (in the 2004 season); however an official plan is not in place. In the following section, a summary of alternative repair methods for stabilizing unreinforced masonry structures will be discussed, followed by an overview of the seismic conditions and building codes applicable to the site at Gordion. In reviewing these key factors, a design proposal for the use and introduction of a formal program of mechanical pinning in conjunction with grout injection is presented as one recommendation for further stabilizing the Early Citadel Gate complex under seismic activity. Furthermore, if the decision is made to only use grout injection without the mechanical pinning, future recommendations are listed at the end of the section for evaluating in situ the efficacy of the current grout injection method.

6.2 Alternative Repair Methods

As previously discussed in Section 3.4, various repair methods have been used for stabilizing historic unreinforced masonry fabric such as underpinning using pilings, stitching, mechanical pinning and chemical anchoring using stainless steel rods fixed in epoxy or other materials which provide a solid bond with the masonry. For the stabilization of the ruins of the early 19th century stone church of the Mission San Juan Capistrano in California, the structural design was based on building response to seismic shaking. For corrosion resistance, the structural systems used stainless steel anchors to anchor new concrete bondbeams to stone masonry by embedding the anchors in epoxy adhesive in holes drilled into stone, and stainless steel rods embedded in cementitious grout using the Cintec anchor system for interconnection of inner and outer wythes through a rubble stone core. Epoxy-coated reinforcing steel was used in the new concrete bondbeams. Lime-based/cementitious mortar was used for repointing and resetting loosened stones. To restrain the top of the tilted east wall of the nave against further tilting, a reinforced concrete bondbeam was embedded. The bondbeam was continued northward and eastward over two walls of the adjacent Transept, and also connected to a new reinforced concrete column near the south end of the wall (the column was concealed inside a stone replica of the original column at that location that had been lost to deterioration). Additionally, at the perimeter of the roof of the sacristy, a reinforced concrete bondbeam ring was constructed to restrain the walls against further tilting and to
support a stainless steel frame over the damaged ceiling vault. The ceiling vault was distorted and had lost most of its capacity to support itself. The original roof had been removed, including a fill of stone rubble and sand between the stone ceiling and the original tile roof. The ceiling was then suspended by stainless steel rods embedded in epoxy adhesive in many holes drilled into the ceiling. The frame was designed to support the entire weight of the stone ceiling, but the loads in the rods were adjusted to allow the ceiling vault to partially support itself to the extent of its capacity. All concrete bondbeams were isolated from the stone masonry by a 1" thick layer of hydraulic lime plaster.\textsuperscript{220} In 1987, cracks caused by water intrusion and frost action at the exterior walls of the medieval rock-cut church El Nazar in the Göreme valley (Cappadocia, Turkey), were structurally consolidated with a grout mixture of epoxy resin and powered local rock.\textsuperscript{221} Use of steel for the interventions to the structural system was deliberately avoided due to the possible negative effects, such as the difference between the coefficients of expansion of the rock and of steel. Selection of the repair method is generally dependent on the current problems or weaknesses of the structure as well as the compatibility of the new system with the original. In the case of the Citadel Gate structure at Gordion, the current problems include the detachment of the limestone block


vener from the rubble core masonry, erosion of the original earthen mortar by intrusion of water through the current cracked concrete capping, and the structure’s position within an area of periodic earthquakes. In order to address this last issue, mechanical pinning has been selected as an appropriate and compatible repair method for stabilizing the structure under seismic activity.

**Figure 6.1.** Earthquake Zoning Map for Turkey in the 1997 seismic code (USC Structural Laboratory website 2006).

### 6.3 Seismic Activity

Turkey is situated on the Eurasian Geological Plate, a highly active plate which has caused several large scale earthquakes throughout history. Since 411 BC, there have
been almost 100 earthquakes which have caused significant losses of life as well as cultural property. Gordion is located approximately 500 km from the North Anatolian Fault Line (NAF) and appears to fall within an earthquake zone IV (Fig. 1) area; where Zone I has the highest earthquake activity and Zone V the lowest. However, regardless of the zone in which the site is situated, its proximity to the NAF has showed tremendous detrimental effects to the structural integrity of the buildings so that precautionary seismic measures should be implemented.

The systemic pattern of earthquakes found along the NAF generally progresses from east to west. Since 1989, there have been nine 7.0 magnitude or larger earthquakes along the NAF, one of the most seismically active right-lateral strike-slip faults in the world (Fig. 6.2). The NAF is a seismically right-lateral strike-strip fault. Strike-strips are faults which move horizontally and are classified as either right-lateral or left-lateral depending on the direction of movement of the block on the far side of the fault.

222 University of Southern California (USC) Structural Laboratory website: http://www.usc.edu/dept/civil_eng/structural_lab/eq-rp/seismicity.html
223 In 1972, the Ministry of Reconstruction and Resettlement updated the earthquake zonation map and the seismic code in 1975 based on new information on geologic structure, plate tectonics, historical seismicity, and earthquake occurrences. This map was revised from the previous 1963 map (representing only four zones) to a newly map which included five zones (Zones I-V). The earthquake zonation map and the seismic code were last updated in 1997 (Structural Engineering Reconnaissance Report Chapter 2 from the National Information Service for Earthquake Engineering (NISEE) website: http://nisee.berkeley.edu/turkey/)
224 USC Structural Laboratory website.
225 Berkeley Seismological Laboratory website: http://seismo.berkeley.edu/seismo/faq/fault_0.html
Specific to the site, significant movement at the bulge on the North Court building was found immediately after the 1999 Izmit earthquake (7.8 Magnitude) that occurred along the NAF. Structural engineer Conor Power indicated that considerable annular movements between 3 and 4 cm occurred at the center of the bulge and displacement of several stones from an exposed section of the core near the west interior corner of the gate complex were results of the seismic activity.\textsuperscript{226} The south wall was thus judged at the time to be dangerously unstable and Power warned of the high risk of structural failure and major collapse after heavy rains.\textsuperscript{227}

In conversation with Nels Roselund, a structural engineer specializing in stabilizing historic structures in California (an area of high seismic activity), the consequence of such ground movement at Gordion can cause the limestone veneer to peel away from the core of the Citadel Gate structure. This is, however, based on the assumption that the

\textsuperscript{227} Ibid. 6.
structure is not constructed of interlocking masonry units (Figs. 6.3 & 6.4) which would greatly contribute to the structural stability during seismic activity. Roselund’s concern here is with whether the veneer is bonded through the core with bond-stones that

interlock the veneer to the core at each side. Bond stones that provide a set of through the wall overlapping stones would tend to restrain the veneer wythes against separation from the core, as well as spreading away from each other. Based on historic and current photographs, the structure does not show the kind of through-the-wall bonding that would be effective. It is virtually impossible to verify the existence of bond-stones without
taking the wall apart, or at least removing a significant area of veneer to look for intentional bonding of the veneer into the core that may indicate through-the-wall bonding. It is most likely that that interlocking has not been constructed into the wall which appears to be a rare form of construction in the United States.228

The relative movement across a strike-slip fault results in seismic ground motions being primarily horizontal with minimal vertical components of shaking. Horizontal shaking perpendicular to a wall will tend to cause the wall to rock on its base. Rocking of a veneered wall can be damaging (see section 6.4 Mechanical Pinning Techniques).

6.3.1 Seismic Codes

Although seismic codes have existed in Turkey since 1940,229 these building codes represent requirements for reinforced concrete structures and do not account for historic buildings and materials. In the state of California where seismic activity is prevalent, the California Building Code regulates both public safety for new construction and the preservation of historic qualities of historic structures in the State Historical Building Code (SHBC). The purpose of the SHBC is to preserve the architectural heritage in

228 Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006. 4.
229 The first seismic code was published as a result of the 7.9 Magnitude Erzincan earthquake in 1939. The calculations of earthquake loads are based similarly to the seismic code used in the U.S. using the Uniform Building Code (ICBO 1997) (Structural Engineering Reconnaissance Report Chapter 2. 9-10). Since 1940, the seismic code and earthquake zonation maps have been revised numerous times until its last publication in 1997.
California by recognizing that there are unique construction problems inherent in historical buildings and allowing use of alternatives to the modern materials and methods mandated by the regular building Code\textsuperscript{230}. Although adoption of a historical building code would be highly advantageous in Turkey since more than 100,000 people have been killed and over 400,000 buildings been destroyed as a result of earthquake activity,\textsuperscript{231} the SHBC is probably not the most applicable. The SHBC does not regulate the details of how to address specific materials or detail of construction, instead it allows more design freedom than the regular Code allows. The intent of the SHBC is not life-safety, but to allow alternative methods to accomplish the life-safety intent of the regular Code when repair and strengthening work is done on structures of archaic construction.

However, there are other codes such as the Uniform Building Code for Building Conservation (UCBC) or the International Existing Building Code (IEBC) which address specific life-safety issues of hazardous buildings which may be more applicable for historical structures in Turkey. Both of these require prescriptive strengthening

\textsuperscript{230} The origin of the State Historical Building Code stems from a 1973 publication of the California History Plan, Volume I, in which Recommendation No. 11 was proposed by the then California Landmarks Advisory Committee. The proposal addressed the need for a new building code which not only protected the health and safety of the public but also maintained “enough flexibility to allow restoration of a Historic feature while still retaining Historic integrity.” After years of meetings and legislation, the first comprehensive regulations were codified in 1979. In 1984 and 1991, changes to the code made the regulations stated by the State Historical Building Code applicable to all qualified historical buildings. The current performance regulations were adopted by the Board in 1998 and approved by the California Building Standards Commission on September 26, 2001 (International Conference of Building Officials. \textit{2001 California Historical Building Code: California Code of Regulations Title 24, Part 8}. California: California Building Standards Commission. 2002. iv).

\textsuperscript{231} University of Southern California Structural Laboratory website: http://www.usc.edu/dept/civil_eng/structural_lab/eq-rp/seismicity.html
procedures for reducing life-safety hazards in building types that are recognized to be hazardous and in need of strengthening. In Turkey, the equivalent to the IEBC or the UCBC would provide specific life-safety enhancing methods for strengthening the building types commonly found in Turkish communities.\textsuperscript{232}

The SHBC is a performance based state regulation for the repairs, alterations, and additions necessary for the preservation, rehabilitation, relocation, related construction, change of use or continued use of a qualified historical building. Additionally, they maintain acceptable life-safety standards and are applicable only if the structure is qualified as a designated historical building or structure defined in Section 18955 as:

\textit{...a qualified historical building or structure is any structure or collection of structures, and their associated sites deemed of importance to the history, architecture, or culture of an area by an appropriate local or state governmental jurisdiction. This shall include structures on existing or future national, state or local historical registers or official inventories, such as the National Register of Historic Places, State historical Landmarks, State Points of Historical Interest, and city or county registers or inventories of historical or architecturally significant sites, places, historic districts, or landmarks.}\textsuperscript{233}

\textsuperscript{232} Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006. 6.

6.4 Mechanical Pinning Techniques

The purpose of mechanical pinning is to use tension resisting devices to interconnect the veneer wythes on both faces of the wall in order to prevent their separation from the core so that the shear strength of the grout can be mobilized. Slight separation of the veneer from the core would disrupt the interlocking provided by the grout. The interlocking of the grout is required in order to mobilize the grouts’ shear strength to keep the wall stable during earthquake shaking. It is the shear strength of the grout that would keep the wall from being broken internally by the veneer sliding downward in relation to the core, and the core from sliding downward in relation to the other veneer face. Stainless steel or fiberglass rods embedded in grout or epoxy adhesive in holes drilled into the wall are the commonly-used tension-resisting devices.234 Tying the walls together will allow the masonry structure to act as one structural unit and during seismic activity permits rocking of the entire wall assembly (Fig. 6.5). Stabilization of a structure can be achieved through a combination of grout injection and mechanical pinning.

Mechanical pinning needs to be accompanied by injection grouting. The hardened grout interlocks the veneer to the core and interlocks the core stones. The pins hold the exterior face of veneer “A” tightly to the core at the plane of contact (interior face of veneer “A”) so that the interlocking by the grout will resist downward slipping of the veneer (Fig.

Likewise, the pins hold the core to the plane of interior face of veneer “B” so that the interlocking grout will resist downward slipping of the core. Without the pins, when the wall rocks onto one edge, as gravity pulls down on the uplifted core and veneer, they will tend to slide downward and seriously damage the wall (Fig. 6.6). The downward sliding will be accompanied by slight spreading of the wall as stones slide and roll across each other. Pins resist the spreading so that the interlocking of the grout is maintained and the shear strength of the grout can resist the downward sliding.\footnote{Nels Roselund. “Additional Comments to page 7 on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006.}

The greatest disadvantage in using mechanical pinning is the loss of original fabric by having to drill holes for the placement of new reinforcement rods. The diameter of the
drilled hole is generally larger for setting pins into grout, with a 1” minimum annular space\textsuperscript{236}.

The repointing of the veneer (as performed in past grout injection campaigns) at the Citadel Gate structure can also help restore the vertical support for stones that may have lost vertical support due to erosion of the mud mortar. As stone bearing on a mud-mortar joint that is almost completely eroded will have lost most of its vertical support, it makes it vulnerable to becoming loose and subject to being shaken from the wall under seismic activity. However, the pointing with new mortar does not need to be very deep, only deep enough to confine the injected grout and keep it from flowing out of the wall. The injected grout will fill voids and surround stones, providing effective vertical support. It is not that the mud mortar is not needed for bonding stones together; it is that it is very ineffective since it probably has a very weak bond strength to the stone\textsuperscript{237}.

As pinning in addition to grouting is needed for effective damage resistance, optimum grout properties such as bond shear strength and splitting tensile strength are important in resisting the rocking damage.

\textsuperscript{236} The annular space is the area between the diameter of the mechanical pin and the diameter of the drilled hole. For example, if using a 1” diameter pin, the diameter of the drilled hole would have to be 3” in order to attain a 1” annular space.

\textsuperscript{237} Since the surfaces of pointing mortars are typically recessed and display an amount of curvature, any downward load received from the masonry distributed throughout the concave surfaces results in a transfer of the compressive load (from the bedding mortar) into tensile strength. Testing the splitting tensile strength for this mortar can be conducted to evaluate its performance under this condition (Nels Roselund. “Repointing of the veneer and Independent wythe masonry.” E-mail to Kelly Wong. April 5, 2006.)
Additionally, the general use of stainless steel and fiberglass rods as well as epoxy or other cementitious mixtures in which the rods are set would introduce a variety of new materials that may not be compatible with the original structure. Incompatibility includes the stiffness of the higher strength reinforcement bars and/or materials they are set in with comparison to the original soft limestone blocks and rubble core. If the new materials are more rigid than the existing fabric, they will have the tendency to outperform the original structure and loss of significant fabric is inevitable. Additionally, corrosion of ordinary stainless steel reinforcement can cause the shattering of even the hardest masonry.\textsuperscript{238} Fiberglass and epoxy each have a rigidity comparable with stone, while stainless steel is much more rigid. However, separation of the steel rod from the stone by grout or epoxy may mitigate the stone/steel incompatibility. Because fiberglass has a lower strength than steel, fiberglass pins may need to be larger than steel pins in order to accomplish the same purpose. Thus, a compromise between the hole size and material compatibility may have to be made.\textsuperscript{239}

An alternative to drilling could be snaking the rods horizontally through the masonry structure without ever having to lose any fabric. However, the problem with this approach would be that bending a tension element makes it flexible. Its rigidity can only


\textsuperscript{239} Nels Roseland. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006. 8.
be fully restored by making it straight. When steel or other materials (e.g. fiberglass) bend, flexibility occurs. However, flexibility is undesirable in pins since they must be rigid enough to prevent separation and loss of the grout interlock. Additionally, depending on the scale of the project, this approach is also highly impractical if not impossible due to the configuration of the core. In the case of the Citadel Gate structure, the rods may never make it through to the other side of the structure because of the rubble fill in the core. This would thus, make mechanical pinning futile. Other alternatives are dismantling the structure, inserting the rods, and rebuilding the wall or reconstructing the Citadel Gate using interlocking stones. These are time consuming and highly unrealistic. Unrealistic because the amount of time it would take to complete tasks would probably be far greater than that allowed to salvage the structure before its collapse.

A realistic approach to mechanical pinning without being completely intrusive to the original structure involves use of a low-impact drilling system. Relton Corporation in California offers special carbide drill bits used specifically for seismic retrofitting and coring through masonry. Drilling using diamond-tipped coring bits also cause minimal vibration in the masonry. In the past 30 years, a range of specifications for mechanical

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240 Ibid.
241 Relton Corporation website: http://www.relton.com
pinning in lengths of 9 meters (30 feet) long have been developed for specific requirements for stabilizing masonry.

The Mission San Miguel in California is currently undergoing mechanical pinning for the stabilization of the adobe structure. In this case, the pins are being installed vertically and are intended to develop horizontal shear resistance at the tops of adobe walls by mobilizing the weight of masonry below the top in order to prevent masonry courses from sliding horizontally during earthquake shaking. A Portland cement-based grout was proposed using Cintec Systems in which grout is injected into nylon netting socks around stainless steel tension rods placed into holes drilled into the masonry. The socks are expanded by the grout to contact the surface of the hole, and grout flow through the sock mesh to bond with the masonry. Subsequently, in order to use a grout that is not as hard and incompatible with adobe as Portland cement grout, a hydraulic lime-based grout was also proposed for San Miguel but this was decidedly too expensive (since the lime was imported from Canada and the cost for developing an appropriate formulation was costly) so the clients declined this option.

Alternatively, an epoxy-sand grout was used for securing the vertically placed mechanical pins. Their placement required pouring the grout from above. The advantage of an epoxy-based grout is the smaller annular space needed and thus, smaller drilled
The system, developed by Progressive Fastening Systems Inc. called for 5/8” diameter rods and 2” diameter drilled holes. A plastic mesh tube with a rigid open tube on top was placed into the drilled holes, followed by the stainless steel rods, and then pouring in the epoxy-sand grout. The grout cures to a hard-rubber hardness that bonds very well to the masonry, an ideal property that allows a slight flexible interconnection between the soft adobe and the rigid steel. The formulation used was 1 part epoxy to 2 parts sand (in volume). Sand was used to slow down the heating of the epoxy. Stainless steel rods were used instead of fiber-glass because of its higher rigidity and lower modulus of elasticity. Another reason an epoxy grout was used in conjunction with stainless steel rods is because prior use of fiberglass rods set in modified mud grout at Pio Pico Mission in California after the 1984 earthquake was found to be significantly damaged after the 1987 earthquake. Both fiberglass rods as well as steel embedments were used at the Pio Pico project. The poor performance at Pio Pico, as observed after the 1994 Northridge Earthquake, had to do with the weakness of the modified mud grout used to embed the rods, not with the fiberglass rods used. According to Roselund, the main advantage of using epoxy includes its ability to bond securely to adjacent materials.

244 Rigidity of a fiberglass rod is approximately 1/10 to 1/20 of a stainless steel rod (Nels Roselund (Structural Engineer, The Roselund Engineering Company). In discussion with the author, March 20, 2006). The modulus of elasticity is a measure of the stiffness of a given material; the ratio of the unit stress to the corresponding unit of strain in an elastic material that has been subject to strain below its elastic limit (Samuel Y. Harris. Building Pathology: Deterioration, Diagnostics, and Intervention. New York: J.Wiley & Sons, Inc., 2001).
The pourable epoxy grout, such as that used at the San Miguel Mission project, is appropriate only for vertical installations. Injection, either before or after installation of the rods would be required for horizontal installations, for a structure such as the Citadel Gate at Gordion. However, disadvantages of using epoxy are its relative high cost, its temperature dependent curing, and the irreversibility. Use for large scale projects such as the Citadel Gate in a location such as central Turkey should be evaluated for its cost-effectiveness.

6.4.1 Design Proposal for Mechanical Pinning

The Citadel Gate complex is a massive structure that stands approximately 10 meters (33 feet) in height with average wall widths spanning about 4 meters (13 feet) thick. Its monumentality is not only found in its overall shear size, but also in the large limestone ashlar blocks used for its veneer and a rubble masonry core of the same material (Fig. 6.7). However, specific dimensions for its ashlar limestone veneer blocks are not given or found in any records. Thus, the design for consolidating the unreinforced masonry structure following the requirements set forth in Chapters 8-7 and 8-8 of the SHBC is only a representation (and estimation) of how mechanical pinning could be used for resisting seismic activity.

According to Section 8-805.2.1 in Chapter 8-8 Archaic Materials and Methods of Construction of the SHBC, stone masonry with independent face wythes\textsuperscript{247} can be treated as a solid brick masonry\textsuperscript{248}, if representative testing and inspection verify that the core is essentially solid in the masonry wall and that steel ties are epoxied in drilled holes.

\textsuperscript{247} “Independent-wythe stone masonry” refers to wythes that are not bonded to adjacent wythes, so that each wythe will tend to act as an independent stack of stones. Thus, it could refer to a two wythe wall, or to two veneer wythes with a third internal wythe consisting of rubble core as in the case of the Citadel Gate structure at Gordion (Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006).

\textsuperscript{248} A solid masonry would prevent separation that would allow internal damage due to loss of grout interlock if the walls should tend to rock because of earthquake shaking. Additionally, it would rock as a unit, while without pinning the wall may act as separate masonry assemblies – each veneer face acting separately from the core (Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006, 12).
between outer stone wythes at floors, roof and at not to exceed 4 feet (1219 mm) on
center in each direction.249

Consideration of historical structures under seismic activity is found in Chapter 8-7
Alternative Structural Regulations, where lateral load regulations are addressed in
Section 8-706 for evaluating resistance of historic structures to wind and seismic
forces.250 Seismic resistance is measured as the ultimate capacity of a structure
(considering ductility and the strength of lateral-force-resisting system and materials)
while maintaining a reasonable degree of safety (Section 8-706.2). For structures which
do not comply with the requirements of the regular code, evaluation for seismic
performance and the consequences for non compliance are required (Section 8-706.2.1).
As discussed earlier, the intent of the SHBC is not life safety but preservation. Life-
safety is the purpose of the regular building code. The SHBC recognized that, in
California, the regular code applies to historic structures as well as new structures, but the
regular code does not tell how to accomplish life-safety using archaic materials like stone
or adobe. The regular code mandates the use of modern materials. Thus, the SHBC
allows the designer of modifications to historic structures to calculate how to achieve

249 International Conference of Building Officials. 2001 California Historical Building Code: California
250 Ibid. 13.
reasonable equivalence to the life-safety intent of the regular code without having to replace archaic materials with modern materials.  

6.4.2 Simulation of Wall Construction

Existing reports and sketches found at the University Museum Gordion archives and photo montages created by former conservation site director Mark Goodman in the 2002-2004 seasons were used to construct the following drawing of the hypothetical wall assembly found at the Citadel Gate structure (Fig. 6.8).

Photographs taken during Young’s excavation seasons in the 1950s and by recent consultants in 2005 show that the Citadel Gate structure is composed of unreinforced wall assemblies with ashlar limestone veneer, a single wythe thick at each face and a rubble masonry core with earthen mortar within. The single wythes are independent of each other and do not have an interlocking construction. The limestone blocks have typical heights of about 1’-0” and varying depths. The illustration above shows the use of horizontal reinforcing bars through a cross-section of a wall (Fig. 6.8). Typical crack widths and voids to be filled by grout are currently unknown but will be investigated in the upcoming Summer 2006 field survey.

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251 Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006, 12.
As mentioned earlier, Section 8 of the SHBC specifies that in order to consider stone masonry with independent face wythes as solid masonry, reinforcement is required using steel ties epoxied and grouted into drilled holes along a grid of 4’-0” on center in each direction regardless of thickness and hardness of stones and regardless of the thickness of the wall (Fig. 6.9). A precise 4ft by 4ft grid of pinning is not necessary. Rods can be recessed into mortar joints on one side of the wall and embedded in holes drilled into [but not through] the veneer on the other side of the wall. The recessed rods on the working

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side of the wall may then be concealed by pointing mortar into the hole drilled into the mortar joint.\textsuperscript{253} Further testing of various rod-adhesive systems will need to be performed specifically for the Citadel Gate context.

\textsuperscript{253} Nels Roselund. “Comments on the Structural Analysis of the Citadel Gate structure.” Email to Kelly Wong. April 5, 2006, 14.
6.5 Future Recommendations

If the decision is made to not to introduce a formal program of mechanical pinning for the stabilization of the Citadel Gate structure, it is recommended that the current method of
grout injection be evaluated for its efficacy. Assessment can include disassembling portions of previously grouted wall sections to inspect the level of adhesion of the grout to adjacent materials (limestone veneer and rubble masonry core) as well as the ability of the specified grout used to fill the voids within the wall assembly. As mentioned earlier, *in situ* non-destructive testing including ultrasonic, sonic vibrational, and flat-jack techniques can be used to evaluate the efficacy of the grout in addition to better understanding the existing wall morphology\textsuperscript{254,255} at the Citadel Gate complex. Since horizontal movements caused by seismic activity can also have effects on the mechanical and structural behavior of multiple-leaf (double wythe) walls – specifically influencing the local conditions in the middle of the wall section (masonry core), bonding characteristics of the walls must be carefully investigated.\textsuperscript{256} Strength tests are also valuable in establishing a better understanding of the chemical-physical and mechanical properties of the grout. Constructed assemblies of the original fabric (limestone) and grout can be used for performing tension strength tests by the simple method of pulling the assemblies apart after specified days (7, 14, 21, 28 days if on site only a short period of time). These tests can at least provide data for the initial strength of the grout and warn of possible problems if they are below accepted levels.


\textsuperscript{256} Ibid. 135.
7.0 CONCLUSION

The results from the Laboratory Experimental Program show that the use of crushed bricks < 75μm in a hydraulic lime-based mixture improves the initial durability and strength of a grout at 28 days cure. The data specifically demonstrates the influence of the proportion used within a mixture and enables a better understanding of the performance and strength of grouts with similar properties such as the one used to currently stabilize the Citadel Gate at Gordion. Limitations of the current research stem mainly from inaccessibility of the site. Without a site investigation, the specific grout formulation used currently to consolidate the Citadel Gate cannot be assessed; the existing wall assembly and its material components which have not been documented also cannot be understood; and thus, the performance of the grout within this structural system cannot be determined or evaluated until a field survey is conducted. Fortunately, a site investigation is scheduled for this summer 2006 to document and assess the conditions at the Citadel Gate, as well as conduct in situ testing of the grout.

7.1 Recommendations

The following recommendations for further research and assessment of the grout used for stabilizing the Citadel Gate are divided into two steps:

1. *In situ* Documentation, Analysis, and Testing (Summer 2006)

2. Future testing and research
7.1.1 *In Situ* Documentation, Analysis, and Testing

A comprehensive site investigation should be conducted in order to better evaluate the performance characteristics of the grout currently used to stabilize the Citadel Gate. Recommendations for the next site investigation include the following:

- **Documentation:**
  - Document the current (typical) wall assembly of the Citadel Gate;
  - Identify existing material components; and
  - Conduct a Conditions Assessment for the Citadel Gate.

- **Testing:**
  - Dismantle part of the wall assembly to evaluate the efficacy of the grout previously used;
  - Assess the bond-shear strength of the grout with the existing veneer and rubble core by constructing test small assemblies *in situ* and evaluating their performance at the end of the excavation season;
  - Conduct an *in situ* flow test (Fig. 7.1);\(^{257}\) and
  - Perform an *in situ* shrinkage test (Fig. 7.2).\(^{258}\)

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\(^{257}\) A flow test using a 2” diameter by 4” long cylinder filled with grout can be held 12” above a ± 6” target and dropped in order to measure flow (Fig. 7.1).

\(^{258}\) *In situ* shrinkage tests, such as filling grout in a container constructed of a similar in material can be easily conducted in the field. For instance, a successful method used in past research has included filling concrete masonry units which are readily available in the United States with grouts using varying proportions of water (Fig. 7.2). Shrinkage characteristics of the grout can then be assessed under the conditions of the application.
**Figure 7.1.** (top) *In situ* flow test (Roselund 2006).

**Figure 7.2.** (bottom) Example of an *in situ* shrinkage test using concrete masonry units (Roselund 2006).
7.1.2 Future Testing

Future testing of the grout formulations should be conducted after analysis and/or acquisition of extant fabric at the Citadel Gate (e.g. existing limestone veneer, rubble masonry, earthen mortar, grout from past injections, and surrounding soils). Upon this analysis, whether \textit{in situ} or in the laboratory, the three grout formulations can be further tested in order to better understand their performance and strengths as applied to the conditions of the site.

The experimental program for Phase II, intended for future testing once further information is gathered from the site investigation and after grout specimens are fully cured at 180 days, is outlined below. Extra grout specimens for salt crystallization and splitting tensile strength have been produced for testing at 180 days cure (on October 16, 2006). Although previous studies have conducted laboratory tests more commonly at 60 days\textsuperscript{259,260} and/or 90 days\textsuperscript{261,262,263} for hydraulic lime-based mixtures, specimens at 180 days,\textsuperscript{264} 120 days,\textsuperscript{265} and/or 360 days\textsuperscript{266} cure have also been tested for strength and

\textsuperscript{262} Bariono et al. (1997).
\textsuperscript{264} Bariono et al. (1997).
\textsuperscript{265} Stewart et al. (2001).
durability. The age for the characteristic strength of natural hydraulic lime mixtures are extended from the customary 28 days for Portland cement to 91 days to take into account the slower rate of strength gain.\textsuperscript{267} Additionally, at 180 days cure, the grout specimens can be tested within the period of the next academic year.

Future testing should include injectibility in the plastic state, salt crystallization resistance, frost resistance, and water vapor transmission to evaluate physical chemical properties, and splitting tensile strength at 180 days, as well as bond shear strength of constructed assemblies at 90 days. See Table 7.1 for the Sample Schedule for Future Testing.

\textsuperscript{266} Baronio et al. (1997).
Table 7.1. Sample Schedule for Future Testing

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Shape</th>
<th>Size</th>
<th>Amount (per formulation)</th>
<th>Total</th>
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<td>Injectibility</td>
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<td>Plexi-glass Cylinder</td>
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<td>3</td>
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<td>Salt Crystallization Resistance</td>
<td>RILEM V.1b</td>
<td>Cube</td>
<td>2”</td>
<td>3</td>
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<td>Frost Resistance</td>
<td>RILEM V.3</td>
<td>Cube</td>
<td>2”</td>
<td>3</td>
<td>9</td>
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<td>Water Vapor Transmission</td>
<td>ASTM E96 (Plastic) Cylinder</td>
<td>1½” dia x 1½” height</td>
<td>3</td>
<td>9</td>
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<tr>
<td><strong>Total Samples</strong></td>
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<td></td>
<td>18 cubes, 18 cylinders</td>
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<tr>
<td><strong>Mechanical Tests</strong></td>
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<tr>
<td>Splitting Tensile Strength</td>
<td>ASTM C496</td>
<td>Cylinder</td>
<td>2” dia. x 4” long</td>
<td>(3) at 120 days</td>
<td>9</td>
</tr>
<tr>
<td>Bond Shear Strength</td>
<td>ASTM D3931</td>
<td>Assembly</td>
<td>2” x 1½” x ¾” thick</td>
<td>(3) at 90 days</td>
<td>9</td>
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<tr>
<td><strong>Total Samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9 assemblies, 9 cylinders</td>
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</table>

Note: This table calculates the number of samples necessary for three grout formulations, in order to test (3) samples per test at ONLY one specified period of time.
APPENDIX A. Literature Review Matrix
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<tr>
<th>Type</th>
<th>Title</th>
<th>Source</th>
<th>Pages</th>
<th>Author</th>
<th>Date</th>
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<td>Location</td>
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<td>Conf</td>
<td>&quot;Ultrasonic pulse transmission: A proposal to evaluate the efficiency of masonry strengthening by grouting.&quot;</td>
<td>2nd International Conference on non-destructive testing, microanalytical methods and environment evaluation for study and conservation of works of art. Perugia 17-20, April 1988. associazione italiana delle prove non intrusiva.</td>
<td>Berra Mario, Binda, Luigia; Baroni, Giulia; and Fatticcioli, Antonio.</td>
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<td>Conf</td>
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<td>Event/Conference</td>
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<td>283-292</td>
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<td>Weaver, Martin E</td>
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<td>Anzani, A., Baronio, G., and Binda, L</td>
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<td>Batis, G.; Chronopoulos, M</td>
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<td>Bouneu, Alain</td>
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Early Phrygian Gate
Gordion, Turkey
Appendix A
University of Pennsylvania
Kelly H. Wong 2006
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<tr>
<td>Journal</td>
<td>In situ consolidation of wall and floor mosaics by means of injection grouting techniques.</td>
<td>Aquileia, Rome: ICCROM.</td>
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<td>Journal</td>
<td>Conserving the ruins of a Hellenistic farmhouse in Crimea, Ukraine.</td>
<td>APT Bulletin 24, no. 2-3.</td>
<td>Jerome, Pamela Weiss, Normen R.; Radel-Salnes, Michela; Crevola, Adina; and Chuseid, Jeffrey Mark</td>
<td>2003</td>
<td>Case Study</td>
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<td>CRM 20, No. 10.</td>
<td>Oliver, Anne</td>
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<td>&quot;Bridging the knowledge gap for safer construction.&quot;</td>
<td>Architecture construction, and conservation of buildings in seismic areas, international seminar, Lima, Peru (May).</td>
<td>Bochana, Jitendra, Himu Shrestha, Bijay Upadhyay, Surya Acharya, Surya Shrestha, Ram Kandel</td>
<td>2006</td>
<td>Seismic</td>
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<td>Site Conservation at Phrygian Gordion (Honors Essay, Department of Art).</td>
<td>Chapel Hill: University of North Carolina.</td>
<td>Rogers, Mark H.</td>
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<td>Gordion, Turkey</td>
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### Appendix A. Grout Ratios from the Literature Review (1982-2005)

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<td></td>
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<td>Trumbanli, 2000</td>
<td>13b-0</td>
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<td>(ancient masonry)</td>
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<tr>
<td>Ignaou, 2003</td>
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<tr>
<td>(mineral grouts for structural consolidation of historical monuments)</td>
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<td>ratio by weight</td>
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<tr>
<td>GERMANY</td>
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<tr>
<td>Strohm, 2009</td>
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<td>(dispersed hydrated lime)</td>
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<td>INDIA</td>
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<td>Sengupta, 1982</td>
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<td>(turbol mass and foundation)</td>
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</table>

**Note:** Ratios are approximate and may vary depending on specific application and conditions.
<table>
<thead>
<tr>
<th>Country</th>
<th>Material &amp; Source</th>
<th>Mixture</th>
<th>Bent</th>
<th>Asbestos</th>
<th>Lime</th>
<th>Sand</th>
<th>Additives</th>
<th>Water Content</th>
<th>Water/Cement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITALY</td>
<td>Peroni et al., 1982 (lime based mortars for repair of historic masonry (OCROMI))</td>
<td>2 (Laferge Chaux Blanche)</td>
<td>4</td>
<td>28</td>
<td>1GI</td>
<td>1GI</td>
<td>Hydrate Rhoosbl</td>
<td>1:20</td>
<td>No Agg</td>
</tr>
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<td></td>
<td>Ferragni et al., 1984 (mural paintings &amp; mosaics)</td>
<td>3</td>
<td>3</td>
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<td>1GI</td>
<td>1GI</td>
<td>Hydrate Rhoosbl</td>
<td>1:10</td>
<td>No Agg</td>
</tr>
<tr>
<td></td>
<td>Mora, 1986 (masonry tuff core, brick &amp; other architectural debris)</td>
<td>4</td>
<td>4</td>
<td>4.5</td>
<td>1GI</td>
<td>1GI</td>
<td>0.15P</td>
<td>2:10</td>
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<td>Morina, 1985 (mosaics)</td>
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<td>4.8</td>
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<td>0.2P</td>
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<td>Mora, 1985 (mosaics)</td>
<td>4</td>
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<td>0.2P</td>
<td>Hydrate Rhoosbl</td>
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<tr>
<td></td>
<td>Binda, 1987 (decayed brick)</td>
<td>M1</td>
<td>4</td>
<td>1</td>
<td>5.28</td>
<td>1:0.25</td>
<td>2.32</td>
<td>1:2.57</td>
<td>M3 No Lime</td>
</tr>
<tr>
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<td>Binda, 1994 (masonry walls)</td>
<td>M2</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1:0.125</td>
<td>1:1.25</td>
<td>1:2.57</td>
<td>M3 No Lime</td>
</tr>
<tr>
<td></td>
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<td>M3</td>
<td>1</td>
<td>1.5</td>
<td>1000 g</td>
<td>1000 g</td>
<td>Hydrate lime &amp; additives</td>
<td>W/C ratio 1.5</td>
<td>W/C ratio 1.5</td>
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<td>M3</td>
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<td>1.5</td>
<td>1000 g</td>
<td>1000 g</td>
<td>Hydrate lime &amp; additives</td>
<td>W/C ratio 1.5</td>
<td>W/C ratio 1.5</td>
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<td>Binda, 1997 (masonry walls)</td>
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<td>1000 g</td>
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<td>Hydrate lime &amp; additives</td>
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Early Phrygian Gate
Gordion, Turkey
Appendix A

University of Pennsylvania
Kelly H. Wong 2006
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<tr>
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<td>university of pennsylvania 188 kelly h. wong 2006</td>
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</tr>
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<td>f6</td>
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<td></td>
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<td>teutonic, 1994</td>
<td>best ratio</td>
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<td>hadrian's wall: performance better with 1 part brick dust (low-fired)</td>
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<td>hydrated lime (buff)</td>
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<td>b3b</td>
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<td>b3c</td>
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<td>lowest % weight loss</td>
<td>1.013</td>
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<td>Percentage</td>
<td>Density</td>
</tr>
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<td>---------------------------------</td>
<td>------------</td>
<td>---------</td>
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<tr>
<td>Lime putty used / 550°C-fired</td>
<td>A2</td>
<td>4</td>
</tr>
<tr>
<td>Lime putty used / 550°C-fired</td>
<td>A3</td>
<td>9</td>
</tr>
<tr>
<td>Lime putty used / 550°C-fired</td>
<td>A4</td>
<td>4</td>
</tr>
<tr>
<td>Lime putty used / 550°C-fired</td>
<td>A5</td>
<td>9</td>
</tr>
<tr>
<td>Lime putty used / 550°C-fired</td>
<td>A6</td>
<td>4</td>
</tr>
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<td>Teutonico, 2003 (hydraulic lime-based mortars)</td>
<td>1</td>
<td>(various hydraulic limes)</td>
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<tr>
<td>Hughes, 2000 (hydraulic lime mortars)</td>
<td>Control Ratio</td>
<td>1 (St. Astier NNL 2)</td>
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<tr>
<td>1:0:3.64 to 1:2:1.54 Test</td>
<td>1</td>
<td>1.5</td>
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<tr>
<td>Lilley, 1967 (rubble masonry)</td>
<td>2</td>
<td>non-specified lime</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goodman, 1984 (lime plaster)</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Roselund, 1990 (modified mud injection for adobe walls)</td>
<td>Rations not specified</td>
<td></td>
</tr>
<tr>
<td>Cancino Jorge, 2001 (lime plaster)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
Early Phrygian Gate
Gordion, Turkey
Appendix A

Legend
- Hydraulic Lime
- Sand
- Cement
- Microspheres
- Brick Dust
- BD = Brick Dust
- Ref. = References sample number in literature

Brick dust (Teunonco 1994)
Porosity more important than firing temperature
Best Quality = Low Fired ≤ 950°C
Low calcination (firing) temp = high hydration rate (Hughes 2000)
- < 38 - 75 μ
- < 300 μ

Smaller particle size
Binder / pozzolan
Speed set
High strength
Low water to mix
Low water vapor transmission

Larger particle size
Porous / particulates
Resistance to frost
Resistance to salt crystallization
Air content
Aids carbonation
APPENDIX B. Laboratory Testing Program Data
A. Grout Mixing Notes

**Batch #1: Formula A**  
**Date: 2/18/06**

<table>
<thead>
<tr>
<th>Formulation A (volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Part (ml)</td>
</tr>
<tr>
<td>De-ionized Water</td>
</tr>
<tr>
<td>1,640 ml</td>
</tr>
</tbody>
</table>

34% water

<table>
<thead>
<tr>
<th>Mixing Times &amp; Water Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Hand mix</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
</tr>
<tr>
<td>8:23</td>
</tr>
<tr>
<td>High</td>
</tr>
<tr>
<td>10:38</td>
</tr>
<tr>
<td>17:37</td>
</tr>
<tr>
<td>24:00</td>
</tr>
</tbody>
</table>

*Doesn’t pass flow test*

<table>
<thead>
<tr>
<th>Speed</th>
<th>Cumulative Time (min:sec)</th>
<th>Cumulative Water Used (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0:00</td>
<td>1,640</td>
</tr>
<tr>
<td>6:43</td>
<td>-</td>
<td>Stop mixing</td>
</tr>
</tbody>
</table>

Total Mixing Time = 24:00 min:sec + 6:43 min:sec = 30:43 min:sec  
Total Water Used = 1,500 ml + 140 ml = 1,640 ml
Batch #2: Formula B  

Date: 2/19/06

### Formulation A (volume)

<table>
<thead>
<tr>
<th>Wet Part (ml)</th>
<th>Dry Part (ml)</th>
<th>Ratio (parts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>De-ionized Water</td>
<td>1 HHL : 3 Sand : 1 Brick Dust</td>
<td>Wet : Dry</td>
</tr>
<tr>
<td>2,050 ml</td>
<td>6,000 ml</td>
<td>1 : 3</td>
</tr>
</tbody>
</table>

34% water

### Mixing Times & Water Used

<table>
<thead>
<tr>
<th>Speed</th>
<th>Cumulative Time (min:sec)</th>
<th>Cumulative Water Used (ml)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand mix</td>
<td>2:00</td>
<td>1,000</td>
<td>Using trowel–for workability</td>
</tr>
<tr>
<td>Low</td>
<td>6:00</td>
<td>1,475</td>
<td>Small air bubbles</td>
</tr>
<tr>
<td>Medium</td>
<td>11:40</td>
<td>1,650</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>15:50</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19:34</td>
<td>1,730</td>
<td>Workability improves</td>
</tr>
<tr>
<td></td>
<td>22:31</td>
<td>1,800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26:45</td>
<td>STOP</td>
<td>Stop mixing</td>
</tr>
</tbody>
</table>

_Doesn’t pass flow test_

<table>
<thead>
<tr>
<th>Speed</th>
<th>Cumulative Time (min:sec)</th>
<th>Cumulative Water Used (ml)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0:00</td>
<td>200</td>
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</tr>
<tr>
<td></td>
<td>8:52</td>
<td>250</td>
<td>Stop mixing</td>
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</tbody>
</table>
Batch #3: Formula C  

Formulation A (volume)

<table>
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<tr>
<th>Wet Part (ml)</th>
<th>Dry Part (ml)</th>
<th>Ratio (parts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>De-ionized Water</td>
<td>1 HHL : 3 Sand : 0.5 Brick Dust</td>
<td>Wet : Dry</td>
</tr>
<tr>
<td>1,850 ml</td>
<td>5,400 ml</td>
<td>1 : 3</td>
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</tbody>
</table>

34% water

Mixing Times & Water Used

<table>
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<th>Speed</th>
<th>Cumulative Time (min:sec)</th>
<th>Cumulative Water Used (ml)</th>
<th>Notes</th>
</tr>
</thead>
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<tr>
<td>Hand mix</td>
<td>3:55</td>
<td>1,360</td>
<td>Using trowel and spatula</td>
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<tr>
<td>Low</td>
<td>5:00</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>8:45</td>
<td>1,600</td>
<td>Workability improves</td>
</tr>
<tr>
<td>High</td>
<td>11:05</td>
<td>-</td>
<td>Lots of air bubbles</td>
</tr>
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<td>14:45</td>
<td>1,720</td>
<td>Grey discoloration</td>
</tr>
<tr>
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<td>17:09</td>
<td>1,790</td>
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<tr>
<td></td>
<td>24:15</td>
<td>1,850</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26:15 STOP</td>
<td></td>
<td>Stop mixing</td>
</tr>
</tbody>
</table>

Passes flow test

Total Mixing Time = 26:45 min:sec + 8:52 min:sec = \textbf{35:37 min:sec}

Total Water Used = 1,850 ml
B. Dry Parts / Water Ratio Calculations (Volume)

**Batch #1: Formula A**

4,800 ml (dry) : 1,640 ml (water)

\[
\frac{4,800}{1,640} = 2.927 \rightarrow 1 \text{ dry : 2.9 wet} \rightarrow \text{approx. 1 dry : 3 wet}
\]

**Batch #2: Formula B**

6,000 ml (dry) : 2,050 ml (water)

\[
\frac{6,000}{2,050} = 2.927 \rightarrow 1 \text{ dry : 2.9 wet} \rightarrow \text{approx. 1 dry : 3 wet}
\]

**Batch #3: Formula C**

5,400 ml (dry) : 1,850 ml (water)

\[
\frac{5,400}{1,850} = 2.919 \rightarrow 1 \text{ dry : 2.9 wet} \rightarrow \text{approx. 1 dry : 3 wet}
\]
## Setting Time Data
### Formulation A

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Time (min)</th>
<th>Penetration Depth (mm)</th>
<th>Average</th>
<th>Notes</th>
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<td>A1 40 40 40 40</td>
<td>40</td>
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</tr>
<tr>
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<td>60</td>
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<td>120</td>
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<td>660</td>
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<td>780</td>
<td>29 26 26 26 26</td>
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<td>840</td>
<td>25 22 20 20 20</td>
<td>22</td>
<td>Initial Set for A1 (14 hr)</td>
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<td>900</td>
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<tr>
<td>16</td>
<td>960</td>
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<td>1020</td>
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Average Initial Set Time = 13.5 hours
Average Final Set Time = 25 hours
Setting Time Data
Formulation B

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</table>

Average Initial Set Time = 9 hours
Average Final Set Time = 15.5 hours
### Setting Time Data

**Formulation C**

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<th>Time (min)</th>
<th>Penetration Depth (mm)</th>
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<td>17</td>
<td>1020</td>
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</tbody>
</table>

Average Initial Set Time = 11 hours  
Average Final Set Time = 16.5 hours
Cured for 14 days

Formulation A – March 4, 2006 (14-day cure)
Formulations B & C – March 5, 2006 (14-day cure)

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (volume)</th>
<th>Wt. dry dish (g)</th>
<th>Wt. wet dish (g)</th>
<th>Wt. liquid grout + wet dish (g)</th>
<th>Wt. liquid grout – wet dish (g)</th>
<th>Wt. cured grout + dish (g)</th>
<th>Wt. cured grout – dry dish (g)</th>
<th>Wt. liquid grout – cured grout (g)</th>
<th>% Weight loss</th>
<th>Mean %</th>
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<tbody>
<tr>
<td>A1</td>
<td>1 HHL : 3 S</td>
<td>129.32</td>
<td>139.66</td>
<td>387.60 (19:15)</td>
<td>247.94</td>
<td>352.60</td>
<td>223.28</td>
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<td>128.37</td>
<td>138.78</td>
<td>388.28 (19:15)</td>
<td>249.60</td>
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<td>382.72 (19:15)</td>
<td>243.00</td>
<td>346.36</td>
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<td>220.00</td>
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HHL – Hydrated Hydraulic Lime  S – Quartz Sand  B – Crushed Brick
## Splitting Tensile Strength Test Results – Data (after 28 day cure)

**Testing Date:** Friday, March 24, 2006

<table>
<thead>
<tr>
<th>Cure Time (days)</th>
<th>Specimen No.</th>
<th>Diameter (in)</th>
<th>Average Diameter</th>
<th>Length (in)</th>
<th>Average Length</th>
<th>Maximum Load (lbf)</th>
<th>Splitting Tensile Strength (kPa)</th>
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<tbody>
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</table>

- Diameter (nearest 0.01 in (0.25mm)), averaging 3 diameters measured near the ends and the middle of the specimen
- Length (nearest 0.01 in (0.25mm)), averaging at least 2 length measurements

**Calculation**

\[ T = \frac{2P}{\pi LD} \]

\[ T = \text{splitting tensile strength, psi (kPa)} \]

\[ P = \text{maximum applied load indicated by machine, lbf (kN)} \]

\[ L = \text{length, in. (m)} \]

\[ D = \text{diameter, in. (m)} \]
## Splitting Tensile Strength Test Results – Data (after 28 day cure)

<table>
<thead>
<tr>
<th>Grout Formula #</th>
<th>Grout Formula Ratio (weight)</th>
<th>Splitting Tensile Strength (psi)</th>
<th>Average Splitting Tensile Strength (psi)</th>
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<tbody>
<tr>
<td>A1</td>
<td>1 HHL : 3 S</td>
<td>34.83</td>
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<tr>
<td>A2</td>
<td>1 HHL : 3 S</td>
<td>30.62</td>
<td>32.73</td>
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<td>A3</td>
<td>1 HHL : 3 S</td>
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</tr>
<tr>
<td>B1</td>
<td>1 HHL : 3 S : 1 B</td>
<td>106.07</td>
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</tr>
<tr>
<td>B2</td>
<td>1 HHL : 3 S : 1 B</td>
<td>64.01</td>
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<tr>
<td>B3</td>
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<td>85.14</td>
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<tr>
<td>C1</td>
<td>1 HHL : 3 S : 0.5 B</td>
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</tr>
<tr>
<td>C2</td>
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<td>42.68</td>
<td>37.73</td>
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</table>

HHL – Hydrated Hydraulic Lime       S – Quartz Sand       B – Crushed Brick

### Splitting Tensile Strength - Sample A1

**Speed 0.1 in/min**

![Graph of Splitting Tensile Strength - Sample A1](image)
Early Phrygian Gate
Gordion, Turkey

Appendix A

Splitting Tensile Strength - Sample A2
Speed 0.1 in/min

Splitting Tensile Strength - Sample B1
Speed 0.1 in/min
Splitting Tensile Strength - Sample B2
Speed 0.1 in/min

Splitting Tensile Strength - Sample B3
Speed 0.1 in/min
Splitting Tensile Strength - Sample C1
Speed 0.1 in/min

Splitting Tensile Strength - Sample C2
Speed 0.1 in/min

Displacement (1 volt = 0.02 in)
Load (1 volt = 100 lbs)

Sample C1
Sample C2
Splitting Tensile Strength - Sample C3
Speed 0.1 in/min

Load (1 volt = 100 lbs) vs. Displacement (1 volt = 0.02 in)

Sample C3
### Confidence Limits Calculations

**Confidence Limits Values**

<table>
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<th>Confidence Level</th>
<th>CL</th>
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<td>0.67</td>
</tr>
<tr>
<td>95%</td>
<td>1.96</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29</td>
</tr>
</tbody>
</table>

### INITIAL SETTING TIMES

**Formulation A**

- **mean value** = 820.0
- **standard deviation**, \( \sigma \) = 17.32

<table>
<thead>
<tr>
<th>Confidence Level</th>
<th>CL</th>
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</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 820.0 ± 6.70</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 820.0 ± 19.60</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 820.0 ± 32.90</td>
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</tbody>
</table>

**Formulation B**

- **mean value** = 560.0
- **standard deviation**, \( \sigma \) = 17.32

<table>
<thead>
<tr>
<th>Confidence Level</th>
<th>CL</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 560.0 ± 0.70</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 560.0 ± 19.00</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 560.0 ± 32.90</td>
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</tbody>
</table>

**Formulation C**

- **mean value** = 650.0
- **standard deviation**, \( \sigma \) = 34.54

<table>
<thead>
<tr>
<th>Confidence Level</th>
<th>CL</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 650.0 ± 13.40</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 650.0 ± 39.20</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 650.0 ± 65.80</td>
</tr>
</tbody>
</table>

### SPLITTING TENSILE STRENGTHS

**Formulation A**

- **mean value** = 32.7
- **standard deviation**, \( \sigma \) = 2.98

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<th>CL</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
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<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 32.7 ± 1.15</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 32.7 ± 3.37</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 32.7 ± 5.66</td>
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</table>

**Formulation B**

- **mean value** = 85.1
- **standard deviation**, \( \sigma \) = 21.03

<table>
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<th>CL</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 85.1 ± 8.13</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 85.1 ± 23.80</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 85.1 ± 39.90</td>
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</tbody>
</table>

**Formulation C**

- **mean value** = 37.7
- **standard deviation**, \( \sigma \) = 4.29

<table>
<thead>
<tr>
<th>Confidence Level</th>
<th>CL</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.67 x 17.32 / ( \sqrt{3} )</td>
<td>= 37.7 ± 1.66</td>
</tr>
<tr>
<td>95%</td>
<td>1.96 x 17.32 / ( \sqrt{3} )</td>
<td>= 37.7 ± 4.85</td>
</tr>
<tr>
<td>99.9%</td>
<td>3.29 x 17.32 / ( \sqrt{3} )</td>
<td>= 37.7 ± 8.15</td>
</tr>
</tbody>
</table>
APPENDIX C. Materials Specifications
Information produit

CHAUx BLANCHE

* Notre offre

Chaux hydraulique naturelle NHL 3,5-Z

* Généralités

Conditionnement : sac de 35 kg

Applications : recommandée pour mortiers et badigeons de façade sur supports tendres, le Chaux Blanche est particulièrement adaptée à la réalisation d'enduits, de mortiers de jointement, de rejointement et de badigeons sur supports tendres du type pierre calcaire et autres maçonnneries anciennes ; coulis d'injection.

Cliquez ici pour consulter les dosages moyens

Vous pouvez compléter votre recherche :
- en consultant la fiche sécurité de ce produit
- en vous adressant à votre direction régionale des ventes
- en accédant à l'Espace Partenaires si vous disposez d'un mot de passe
FICHE DE DONNEES DE SECURITE DES CHAUX DE CONSTRUCTION
Chaux hydraulique naturelle NHL ou NHL-Z
visées par la Norme NF EN 459
conforme au décret du 03/12/92, modifié par le décret du 01/03/94, et à l’arrêté du 05/01/93

I - IDENTIFICATION DU PRODUIT ET DE LA SOCIETE

1.1 Produit : Chaux hydraulique naturelle NHL ou NHL-Z, visée par la norme NF P 15-311
Utilisations : Enduits, badigeons, mortier, coulis d’injection.
Nom commercial : CHAUX BLANCHE, TRADIFARGE, CRUALYS

1.2 Identification du fabricant :
Nom : LAFARGE CIMENT
Adresse : 5 bd Louis Loucheur – 92214 SAINT-CLOUD CEDEX
Tél : 01.49.11.40.40 Télécopie : 01.49.11.01.04

1.3 En cas d’urgence : ORIFILA, tél : 01 49 42 36 39

II - INFORMATION SUR LES COMPOSANTS

La chaux hydraulique naturelle résulte de la cuisson à environ 1200°C de calcaires siliceux. Elle est composée principalement de silicates de calcium, d’aluminales de calcium et d’hydroxyde de calcium produits par la calcination et de calcaire argileux ou siliceux, suivie de l’extinction.

Le contact de l’eau, elle a la propriété de faire prise et de durcir. Le dioxyde de carbone présent dans l’air contribue également au processus de durcissement. Elle contient au moins 12 % en masse de chaux libre non liée.

La chaux obtenue par la calcination de calcaire plus ou moins argileux ou siliceux, avec réduction en poudre par filtre, est appelée « chaux hydraulique naturelle » (NHL). La chaux hydraulique naturelle, à laquelle on a ajouté de façon appropriée des matériaux pulvérisés ou hydratés jusqu’à 20 %, est désignée par NHL-Z.

Les composants NHL et NHL-Z peuvent contenir des additifs organiques en faibles quantités. Les additifs ne doivent pas avoir aucun effet nuisible sur les propriétés des mortiers.

III - IDENTIFICATION DES DANGERS

La chaux hydraulique naturelle n’est pas classée comme « préparation dangereuse » selon les dispositions de l’annexe VI de la directive 67 / 546 / CEE. Cependant, en raison de son caractère basique en solution, on doit prendre des précautions pour la manipuler.

<table>
<thead>
<tr>
<th>Symbole de danger</th>
<th>Principaux dangers pour l’homme et l’environnement</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>• La chaux hydraulique naturelle est irritante pour les yeux, pour les voies respiratoires, les muqueuses et la peau du fait d’une hydratation partielle et du pH élevé qui en résulte.</td>
</tr>
<tr>
<td></td>
<td>• Risques de lésions cutanées graves en cas de projection de poudre ou de pâte dans les yeux.</td>
</tr>
<tr>
<td></td>
<td>• Lors du gâchage, la chaux hydraulique naturelle présente un pH élevé ; elle peut alors intervert et dessécher la peau.</td>
</tr>
<tr>
<td></td>
<td>• Un contact prolongé avec la peau peut entraîner une sensibilisation due à une hydratation partielle et au pH élevé qui en résulte.</td>
</tr>
<tr>
<td></td>
<td>• En cas d’inhalation significative, la chaux hydraulique naturelle est caustique pour le tractus digestif. Elle peut entraîner des brûlures de la bouche, de l’œsophage et de l’estomac.</td>
</tr>
<tr>
<td></td>
<td>• La chaux hydraulique naturelle ne présente pas de risque particulier pour l’environnement sous réserve de respecter les recommandations de la section XIII relatives à l’élimination ainsi que les prescriptions réglementaires nationales ou locales pouvant s’appliquer.</td>
</tr>
</tbody>
</table>

N° de version : 3.1
N° de modification : 1
Mise à jour : février 2004
IV - DESCRIPTION DES PREMIERS SECOURS À PORTER EN CAS D'URGENCE

Contact avec les yeux : • Rincer immédiatement et abondamment à l'eau propre et consulter un ophtalmologiste.

Contact avec la peau : En cas de contact prolongé avec la peau :
• Si la chaux hydraulique naturelle est à l'état sec, éliminer au maximum la poussière de chaux, puis laver abondamment à l'eau.
• Si la chaux est gélée, laver abondamment à l'eau.
• Pratiquer garde au produit pouvant subsister entre la peau et les vêtements, la monce, les chaussures.

Inhalation : En cas d'inhalation de grandes quantités de poussières de chaux hydraulique naturelle :
• Amener le sujet en dehors de la zone empoissée, consulter un médecin s'il existe une gêne respiratoire.

Ingestion : En cas d'ingestion significative :
• Rincer la bouche, faire boire de l'eau et consulter un médecin.

V - MESURES DE LUTTE CONTRE L'INCENDIE
La chaux hydraulique naturelle n'est pas inflammable.
Tous les agents d'extinction sont utilisables en cas d'incendie à proximité.

VI - MESURES À PRENDRE EN CAS DE DISPERSION ACCIDENTELLE

Précautions individuelles :
• Éviter tout contact avec les yeux.
• Éviter le contact avec la peau.
• Éviter de respirer les poussières.
• En cas d'envolées de poussières, porter un masque anti-poussières adapté.
• Manipuler le produit avec des vêtements appropriés (gants, combinaison, bottes...).

Protection de l'environnement :
• Éviter de déverser de la chaux hydraulique naturelle en quantité importante dans les rigouts et dans les eaux de surface.
• Ramasser sans délai tout épanagement accidentel en quantité significative sur un sol.

Méthodes de nettoyage et de récupération du produit :
• Privilégier le ramassage de la chaux hydraulique naturelle par un moyen approprié permettant d'éviter les envolées de poussières.
• Après la prise, la chaux hydraulique naturelle peut être évacuée comme un déchet banal du bâtiment. La chaux hydraulique naturelle durcit après avoir été mélangée à l'eau après un temps variable qui n'est jamais inférieur à 1 heure.

VII - PRÉCAUTIONS DE STOCKAGE, D'EMPLOI ET DE MANIPULATION

<table>
<thead>
<tr>
<th>STOCKAGE</th>
<th>EMPLOI</th>
<th>MANIPULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Tenir hors de portée des enfants.</td>
<td>• Éviter l'envolée de poussières de chaux hydraulique naturelle lors de l'utilisation. Si elle ne peut être évitée, porter un masque anti-poussière.</td>
<td>• La manipulation de la chaux hydraulique naturelle en vrac doit se faire par des moyens appropriés pour éviter les envolées de poussières.</td>
</tr>
<tr>
<td></td>
<td>• Éviter le contact direct de la chaux hydraulique naturelle avec la peau et les muqueuses.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Le port de lunettes de sécurité est conseillé.</td>
<td></td>
</tr>
</tbody>
</table>

VII - PROCEDURES DE CONTROLE DE L'EXPOSITION DES TRAVAILLEURS ET CARACTERISTIQUES DES EQUIPMENTS DE PROTECTION INDIVIDUELLE

6.1 - Contrôle de l'exposition :
- valeurs limites d'exposition aux poussières (article R.232-5-5 du Code du travail):

<table>
<thead>
<tr>
<th>Poussières totales</th>
<th>10 mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poussières aériennes</td>
<td>5 mg/m³</td>
</tr>
</tbody>
</table>

Mise à jour février 2004
8.2 - Protections individuelles :

Protection respiratoire : en présence de poussières de chaux hydratique naturelle dans l'air, l'utilisation d'un masque anti-poussières est recommandée.

Protection des mains : porter des gants imperméables doublés intérieurement de coton.

Protection des yeux : porter des lunettes de protection en cas de risques d'envoûes de poussières ou en cas de risques de projection de poussière ou de pâte dans les yeux.

Protection de la peau : porter des vêtements adaptés au type de travail (combinaison) et qui protègent les avant-bras en continuité avec les gants. Pour le travail à genoux, des genouillères imperméables sont recommandées. Des crèmes "barrière" peuvent être utilisées. Le port de bottes (chaussures étanches) est conseillé. Se laver abondamment en cas de contact.

X - PROPRIÉTÉS PHYSICO-CHIMIQUES

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Poudre blanche.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odeur</td>
<td>Inodore.</td>
</tr>
<tr>
<td>pH en solution aqueuse</td>
<td>Blasique entre 12 et 13.</td>
</tr>
<tr>
<td>Température de fusion</td>
<td>&gt; 1000°C.</td>
</tr>
<tr>
<td>Masse volumique absolue</td>
<td>2.6 g/cm³ à 20°C.</td>
</tr>
<tr>
<td>Masse volumique apparente</td>
<td>0.65 g/cm³ à 20°C.</td>
</tr>
<tr>
<td>Solubilité dans l'eau</td>
<td>Jusqu'à 1.5 g/l à 20°C.</td>
</tr>
<tr>
<td>Point d'éclair</td>
<td>Non applicable.</td>
</tr>
<tr>
<td>Température d'inflammation</td>
<td>Non applicable.</td>
</tr>
<tr>
<td>Danger d'explosion</td>
<td>Néant.</td>
</tr>
<tr>
<td>Granulométrie</td>
<td>De l'ordre de 20 à 30 % de fines &lt; 5 μm.</td>
</tr>
</tbody>
</table>

X - STABILITÉ ET REACTIVITÉ

| Stabilité              | Le produit est stable. |
|                       | L'humidité peut provoquer la prise de la chaux hydratique naturelle. |
| Matières à éviter      | Néant. |
| Produits de décomposition dangereux | Néant. |
| Remarque               | La prise de la chaux hydratique naturelle s'accompagne d'une légère élévation de la température. |

XI - INFORMATIONS TOXICOLOGIQUES

| Inhalation             | La chaux hydratique naturelle peut provoquer une irritation des voies respiratoires. |
|                       | La chaux hydratique naturelle peut provoquer une inflammation de la muqueuse nasale. |
|                       | Dans des cas extrêmes, on a pu observer des éruptions de la muqueuse. |
| Ingestion              | En cas d'ingestion significative, la chaux hydratique naturelle peut provoquer des débries de la bouche, de l'oesophage et de l'estomac. |
| Contact avec la peau   | La chaux hydratique naturelle peut irriter la peau humide par hydration partielle entraînant un pt érode. |
|                       | Un contact prolongé avec de la chaux hydratique naturelle gâchée peut provoquer une brûlure de la peau (C1/5-1/5). |
| Contact avec les yeux  | La chaux hydratique naturelle peut entraîner une irritation des paupières et provoquer des lésions graves des globes oculaires qui justifient un lavage prolongé et une consultation ophtalmologique. |
| Pathologie chronique cutanée | L'exposition prolongée sans protection adaptée (gants) peut provoquer une dermatite d'irritation. |
| Cancérogénicité        | Non répertorié. |
| Genotoxicité           | Non répertorié. |

Mise à jour février 2004
XII - INFORMATIONS ECOLOGIQUES

Écotoxicité :

- En cas de déversement accidentel dans des eaux résiduelles, la poudre de chaux entraîne une faible élévation du pH de l'eau. La chaux hydraulique naturelle hydratée est un matériau stable qui fixe définitivement ses composés et sont inéloisibles.

Mobilité :

- Néant.

Persistante et dégradabilité :

- Néant.

Potentiel de bio-accumulation :

- Néant.

Effets nocifs divers :

- Néant.

XII - INFORMATIONS SUR LES POSSIBILITÉS D'ÉLIMINATION DES DÉCHETS

Après la prise, la chaux hydraulique naturelle peut être éliminée comme les autres résidus de construction et stockée dans des décharges appropriées en respectant la réglementation en vigueur.

XIV - INFORMATIONS RELATIVES AU TRANSPORT

Marchandise non dangereuse au regard de la réglementation des transports.

XV - INFORMATIONS REGLEMENTAIRES

<table>
<thead>
<tr>
<th>Symbole de danger :</th>
<th>X, produit irritant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituant principal :</td>
<td>Chaux</td>
</tr>
<tr>
<td>Phrases R :</td>
<td>R36/37/38 Irritant pour les yeux, les voies respiratoires et la peau (Cr³⁺). R41 Risques de lésions oculaires graves.</td>
</tr>
<tr>
<td>Maladies professionnelles</td>
<td>Code de la sécurité sociale : non répertorié.</td>
</tr>
<tr>
<td>Maladies à caractère professionnel</td>
<td>Code de la sécurité sociale : insuffisantes.</td>
</tr>
</tbody>
</table>

Surveillance médicale spécialisée : Non concerné.

XVI - AUTRES INFORMATIONS

Cette fiche de données de sécurité remplace celle de janvier 2002 et février 2003.

Les renseignements susmentionnés et les présentes doivent être utilisés dans le cadre des connaissances relatives à la chaux hydraulique naturelle. Ils sont donnés de bonne foi.

En aucun cas, ces informations ne sauraient être prises comme des garanties de qualité.

L'attention des utilisateurs est attirée sur le risque éventuellement encouru lorsqu'un produit est utilisé à d'autres usages que celui pour lequel il est conçu. Il est de la responsabilité de l'utilisateur de déterminer les mesures de sécurité appropriées et d'appliquer l'ensemble des textes réglementant son activité. Les prescriptions mentionnées dans cette fiche ont pour but d'aider l'utilisateur à remplir les obligations qui lui incombent. Les recommandations énumérées ne peuvent être considérées comme exhaustives.

Mise à jour février 2004

LaFARGE
Ciments

Page 4 sur 4
YELLOW BAR SAND
Specifications
Provided by: Cava Building Supply
January 2006

Dun-Rite
SAND AND GRAVEL COMPANY

Test taken on May 13, 2005
Cava Building Supply
Attn: Dominic
Re: ASTM C-144
Project:

Gentlemen:
This letter is our certification that the Bar sand supplied by Dun-Rite Sand & Gravel Co. to your company meets ASTM C-144, and Penn Dot's Table A Fine Aggregate Type C specifications;
The following gradation is listed below: (Plant #4)

BAR SAND

<table>
<thead>
<tr>
<th>STEVE</th>
<th>% PASSING</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>00.7</td>
</tr>
<tr>
<td>30</td>
<td>72.4</td>
</tr>
<tr>
<td>50</td>
<td>32.2</td>
</tr>
<tr>
<td>100</td>
<td>2.9</td>
</tr>
<tr>
<td>200</td>
<td>.1</td>
</tr>
</tbody>
</table>

Material inorganic and non plastic
If there are any further questions, feel free to contact me at (836) 825-9900.

Respectfully yours,
Ronald Fusloski
Sales Manager
YELLOW BAR SAND
Specifications
Provided by: Cava Building Supply
January 2005

DUN-RITE
SAND AND GRAVEL COMPANY

OFFICE AND MAILING ADDRESS
373 East Grant Ave.
Villanova, New Jersey 08080-2229
Phone: (609) 561-2013
Fax: (609) 561-9150

Plant #1
500 Dutch Mill Rd
Monroe Twp, NJ 08052-9341
Phone: (609) 561-2013
Fax: (609) 561-9150

Material Safety Data Sheet
March 18, 2005

Cava Building Supply
Attn: Dominic

Re: Bar Sand
Project: (lds)

Plant #4
3755 Mayo Landing Rd
Villanova, NJ 08080-2229
Fax: (609) 561-9150

Item: Crystalline Silica
Chemical Components: Silica, Crystalline Quartz (respirable)
Composition: SiO2: 95%

Physical / Chemical Characteristics
- Boiling Point: 4046°F
- Specific Gravity: 2.55
- Melting Point: 3050°F
- Vapor Pressure: None
- Evaporation Rate: None
- Vapor Density: None
- Solubility in Water: Insoluble
- Appearance: White, Tan, Orange or Brown
- Odor: No taste or odor

Permissible Exposure Limits: Exposure airborne crystalline shall not exceed
an 8 hour time weighted average (TWA) limit as stated in 29CFR1910.1000
- Flammable Limits: Material Non Flammable to
- Reactivity Limits: Material Non Reactive

Steps to be taken in case material is released or spilled: Use dustless methods, water or wet HPRC-type vacuum, if not contaminated. Use water sprays and shovels to clean up spills. Do not dry sweep with broom, do not use compressed air. Dispose in accordance with federal, state and local regulations.

The information contained in this safety data sheet is believed to be correct. Dun-Rite Sand & Gravel makes no warranties and assumes no liability in connection with any use of this information. Users of this product must comply with all applicable federal, state and local regulations and must seek professional opinions regarding their use and hazards.
APPENDIX D. Testing Standards
Early Phrygian Gate
Gordion, Turkey
Appendix D

<table>
<thead>
<tr>
<th>TRUE *</th>
<th>Hardening only in contact with CO₂ in the air (Carbonation) Classified according to their Calcium oxide/magnesium oxide content (50, 65, 60, 70)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLD New</td>
<td><strong>Main components</strong></td>
</tr>
<tr>
<td>Quicklime</td>
<td><strong>Calcium Oxide + Magnesium Oxide</strong> calculated and producing an exothermic reaction in contact with water</td>
</tr>
<tr>
<td>CAEB CL (calcium lime)</td>
<td>Calcium oxide or Calcium Hydroxide</td>
</tr>
<tr>
<td>DL (dolomitic lime)</td>
<td>Calcium and Magnesium Oxides OR Semi hydrated and hydrated Calcium and Magnesium Hydroxides</td>
</tr>
<tr>
<td>Hydrated lime</td>
<td>CL or DL resulting from controlled slaking of quicklime. Produced as POWDERPUTTY or SLURRY (milk of lime)</td>
</tr>
</tbody>
</table>

**Hydraulic Lime** - Setting and hardening in contact with water. Air setting also present. Classified according to Compressive Strength expressed in N/mm² measured @ 28 day in mortars prepared with 1:1.5 trinidad/sand ratio.

<table>
<thead>
<tr>
<th>OLD</th>
<th>NEW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eminently Hydraulic</strong> or XHN 100</td>
<td><strong>NHL 5</strong></td>
</tr>
<tr>
<td><strong>Moderately hydraulic</strong> or XHN 60</td>
<td><strong>NHL 3.5</strong></td>
</tr>
<tr>
<td><strong>Feebly hydraulic</strong> or XHN 30</td>
<td><strong>NHL 2</strong></td>
</tr>
</tbody>
</table>

**ARTIFICIAL HYDRAULIC LIME** or XHA

| Hydraulic Limes | **HL** | A blend of calcium hydroxide, calcium silicate and calcium aluminates (and possibly other materials such as ash, fillers etc.) N.D.R. |

**NOTES:** Artificial hydraulic limes (HL) are not regulated in their overall composition and the presence of cement is almost certain. A more appropriate definition would have been **HB (Hydraulic Binders)** instead of HL. Should be avoided in restoration and conservation work. The addition permitted in NHL-Z of up to 20% of other materials in conjunction with the further allowances made in the Norm related to the presence of SO₃ (3% AND UP TO 7% subject to soundness test) and the small amount of Available Lime required in NHL products (3% - 15%)* can cause problems. These additions will consist of cement or other materials (i.e. Gypsum) used in order to achieve constancy in the performance of otherwise unreliable products. Although in many instances this will be acceptable in new build. in restoration and conservation work NHL-Z products could produce unwanted effects.

* Available lime in St. Aistir NHL products: 15% to over 50%
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University of Southern California (USC) Structural Laboratory Website:
http://www.usc.edu/dept/civil_eng/structural_lab/eq-rp/seismicity.html

Archival Collections

University of Pennsylvania Museum of Archaeology & Anthropology, Gordion Archives,
Philadelphia, Pennsylvania
Photographs, Slides, Maps, and Journal Articles (Publications)
Drawings of Gordion, Turkey Site


2004. Yassihöyük/Gordion Early Phrygian Period YHSS 6A (plan showing excavated building footprints) by Carrie Alblinger.

2004. Yassihöyük/Gordion Early Phrygian Destruction Level YHSS 6A (plan showing areas under construction, drains, and limits of excavation) by Carrie Alblinger.

2004. Yassihöyük/Gordion Middle Phrygian Period YHSS 5 (plan showing excavated building footprints) by Carrie Alblinger.

Personal Interviews

Gareth Derbyshire (Rodney Young Fellow, University of Pennsylvania Museum of Archaeology & Anthropology). In discussion with the author, date.

Frank G. Matero (Chair and Professor, Graduate Program of Historic Preservation at the University of Pennsylvania). In discussion with the author, 30 November 2005.


Kenneth Sams (Director of the Gordion Archaeological Project, University of North Carolina at Chapel Hill). In discussion with the author, March 25, 2006.


Mary Voigt (Excavation Director, Gordion Archaeological Project, College of William & Mary). In discussion with the author, April 1, 2006.
GLOSSARY

ashlar masonry – masonry composed of rectangular units of burnt clay or shale, or stone, generally larger in size than brick and properly bonded, having sawn, dressed, or squared bed and joints laid in mortar.

chinking – the material used to fill chinks *i.e. long cracks, openings, or fissures) such as between large masonry blocks that form the exterior walls of a masonry wall construction. Where the cracks are small, the filling material is often mud or plaster; where the cracks are large, the filling may include pebbles, straw, or small stones.

compression – the state of being compressed, or being shortened by force; the change in length produced in a test specimen by a compressive load.

consolidation – the process whereby particles are packed more closely by the application of continued pressure.

cross-section – a representation of a structure, or portion thereof, drawn as if it were cut vertically to show its interior; often taken at right angles to the longitudinal axis of the structure.

delamination – failure in a laminated structure, characterized by the separation or loss of adhesion between piles, as in built-up roofing or glue-laminated timber.

diametral – of or pertaining to the diameter.

differential movement – relative movement of different parts of a structure caused by uneven sinking of the structure.

ductile – capability to be stretched or deformed without fracturing.

durability – the ability of a material, component, assembly, or building to resist weathering action, chemical attack, abrasion, and other conditions of service.

grout – a thin mortar containing a considerable amount of water so that it has the consistency of a viscous liquid in order to be poured or pumped into joints, spaces, and cracks within masonry systems.

grouting – the process of injecting fluids that set into cracks or voids used commonly to consolidate or strengthen a structural system.
**hydraulic hydrated lime** - the hydrated dry cementitious product obtained by calcining a limestone containing silica and alumina, or a synthetic mixture of similar composition, to a temperature short of incipient fusion so as to form sufficient free lime (CaO) to permit hydration and at the same time leaving unhydrated sufficient calcium silicates to give the dry powder, meeting the requirements herein prescribed, its hydraulic properties.

**laitance** – a surface skin that develops on over-worked mortar surfaces, drawing fine material to the surface and reducing permeability.

**modulus of elasticity** – the ratio of the unit stress to the corresponding unit of strain in an elastic material that has been subject to strain below its elastic limit.

**mortar** – any material which can be worked or placed in a plastic state, becomes hard when in place, and which can be used for bedding, jointing or finishing the materials forming the component parts of a wall.

**permeability** – the property of a porous material that permits the passage of water vapor through it.

**Portland cement** – the common form of cement made by grinding clinker formed by firing clay and limestone at high temperatures.

**porosity** – a ratio, usually expressed as a percent of the volume of voids in a material to the total volume of the material, including the voids. The voids permit gases or liquids to pass through the material.

**pozzolans** – materials containing fine particles of reactive silica and alumina, and sometimes iron oxides, which will react with calcium hydroxide and water to produce a chemical set in mortar, similar to the set achieved by hydraulic limes.

**rheology** – the science dealing with flow of materials, including studies of deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries, pastes, and the like.

**rubble stone masonry** – stone masonry composed of irregularly shaped units bounded by mortar.

**seismic** – of or caused by an earthquake.

**shear** – a deformation in which parallel planes slide relative to each other so as to remain parallel.
**shrinkage crack** – a crack caused by restraint of shrinkage.

**tension** – the state or condition of being pulled or stretched.

**tensile strength** – the resistance of a material to rupture when subject to tension; the maximum tensile stress which the material can sustain.

**viscosity** – the internal frictional resistance exhibited by a fluid in resisting a force that tends to cause the liquid to flow.

**wythe** – each continual vertical section of wall, one masonry unit in thickness.
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