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Strength of Masonry Grout Made with Expanded Shale

Allison Tanner

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Strength of Masonry Grout Constructed with Light-weight Aggregate

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Light-weight aggregate has been used successfully for structural and non-structural applications, and its most common use has been in light-weight concrete. Limited research has been done on light-weight grout though and there are no standards in place. The research performed in this study is intended to increase the knowledge of light-weight grout specifically made with expanded shale aggregate.

The research presented herein is a pilot study and consists of preliminary aggregate and grout testing that resulted in the mix design of six grout types: three fine grout designs and three coarse grout designs. Conventional normal-weight aggregate was employed in the first grout mix. A light-weight aggregate batch was made with the same material proportions, as well as the same target water-cement (w/c) ratio and cement content. The weight of the cement was increased by 30 percent in the third grout type of each set to determine the effect on strength. The slump, component temperature, unit weight, air content, segregation, cement content, w/c ratio, and compressive strength for each grout type was gathered throughout testing.

Correlations between grout testing results are examined and discussed. In addition, the effectiveness of expanded shale grout, other light-weight grouts, and normal-weight grout with respect to compressive strength to cement content ratio are determined.

Results of the testing show that all six grout types studied in this research reached the minimum 28-day strength of 13.8 MPa (2000 psi) ASTM standard. In addition, the results indicate that the cement content in expanded shale light-weight grout would need to be increased to reach comparable compressive strengths to that of the normal-weight grout. The comparison between the compressive strength to cement content ratio of the different grouts indicate that normal-weight grout is more efficient. In addition, light-weight grout made with blast furnace slag grout is slightly more efficient than that made with expanded shale; however, this observation was only possible after several crucial assumptions were made about an existing blast furnace slag study. These strength-cement ratios do not account, however, for the benefits of reduced dead loads, improved thermal insulation, and improved sound insulation that could potentially influence the choice of the material used in and the life-cycle cost of the construction. Additional research should be done to verify the results of the ratios and the assumptions made herein. Furthermore, a life-cycle analysis needs to be conducted before a definite conclusion is made about which type grout is more efficient.

Keywords: Light-weight aggregate, light-weight grout, compressive strength, water-cement ratio, expanded shale

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1 INTRODUCTION

1.1 Fundamentals

Masonry is one of the oldest methods of building construction. The common components of current masonry construction are masonry units, mortar, grout, and reinforcing steel. The strength of the masonry structure is dependent on the interaction between these components. The compressive strength of grout is important for quality control and the strength of the masonry system.

Masonry units are made with a variety of materials including concrete, clay and glass. The desired masonry unit material is determined based on requirements for aesthetics, strength, durability, and availability, and any other characteristics deemed important by the owner. Masonry units usually have holes or cells cut into them that are often filled with grout and reinforcement for increased axial and shear capacity.

Cells in masonry units are filled with grout to increase capacity and to hold reinforcing steel in place [18]. Grout for masonry construction is a high slump mixture of cementitious materials, aggregate and water. Grout is required to have a slump of 200 to 280 mm (8 to 11 inches) to ensure a flowable mixture. This is important because grout must be able to consolidate easily in small cell areas and around reinforcement without leaving voids. Since grout spaces are small, aggregate should be chosen accordingly [18]. Grout is classified into two types: fine and coarse. Coarse grout includes both coarse and fine aggregate while fine grout only includes fine aggregate.

Aggregate can be normal-weight, the typical aggregate used, or light-weight. The most common types of light-weight aggregate used in structural concrete are expanded clay, shale, or slate [20]. Expanded shale from Utelite Corporation is used in this research project. Raw shale is quarried, crushed, screened, and processed into expanded shale. The raw shale is passed through a kiln that is heated to a temperature of approximately 1093° C (2000° F). At this temperature the material will bloat because the internal gases are trying to escape. The material is red hot and somewhat plastic which lowers the viscosity of the material and allows it to expand. This expansion creates small non-interconnecting internal voids, which remain after the material cools and solidifies [24].

1.2 **Motivation**

Light-weight aggregate is currently used for many concrete applications, commonly buildings and bridges. Light-weight material has also been used in the manufacturing of concrete masonry units (CMU) but light-weight material is not commonly used for masonry grout. Most likely, the benefits of using light-weight grout would be similar to those observed from using structural light-weight concrete. Light-weight aggregates are generally more expensive than normal-weight aggregates, but the increased strength-to-weight ratio offers sufficient overall saving in materials. The reduction of dead load also offsets the higher aggregate cost per cubic meter of the concrete, and lower total loads mean reduced supporting sections and foundations, and less reinforcement [20].

There are no standards for light-weight grout and previous research on structural light-weight masonry grout is extremely limited. The use of blast furnace steel slag to produce structural masonry grout was studied by Petty and Nelson [22]. That study determined that the grout made with blast furnace steel slag achieved the ASTM C476 compressive strength requirements [10]. The authors of that study did not specify if materials were proportioned by weight or volume and did not include information about the grout water-cement (w/c) ratio. This information is vital for being able to compare their results to other light-weight grout studies.

Since research on light-weight grout is so limited, a pilot experimental program to expand the knowledge base on light-weight grout was designed. For the first time, expanded shale aggregate was used as aggregate material in masonry grout and tested. The main objective of this study was to determine if light-weight grout made with expanded shale meets the ASTM C476 compressive strength requirements [10]. The research included testing light-weight grout and normal-weight grout so that compressive strengths and cement contents could be compared between the aggregate types.

1.3 **Scope**

A testing program was conceived involving testing light-weight and normal-weight aggregates to determine their properties and then designing, manufacturing, and testing light-weight and normal-weight grout variations. The aggregate was first tested for absorption, moisture content, and specific gravity. These properties were then employed in designing grout with a target slump between 200 to 280 mm (8 to 11 inches) and a target 28-day compressive strength of 13.8 MPa (2000 psi).

The experimental program presented herein to test grouts made with expanded shale was designed so that researchers could make meaningful comparisons between light-weight grout and normal-weight grout results. In the research presented herein cement content and w/c ratio were controlled while slump was allowed to vary. Cement content was controlled to determine the effects of cement content on the grout compressive strength. Also, the w/c ratio was held as constant as possible between fine and coarse grout so that compressive strength results were an outcome of the aggregate used, the cement content, and the bond characteristics of the aggregates instead of the w/c ratio.

Six variations of grout were batched and tested. Normal-weight aggregate was used to make a batch of fine and coarse grout. Light-weight aggregate was used to make a batch of fine and coarse grout with the same w/c ratio and cement content and then another batch with the same w/c ratio and an increased cement content. Grout testing was performed to determine the slump, unit weight, air content, and segregation. Four grout cylinder specimens were made with each grout and the cylinders were allowed to cure for 28 days. After 28 days the specimens were tested to determine their compressive strength.

1.4 **Outline of Thesis**

This thesis contains eight chapters. Chapter 1 is an introductory chapter that presents the objectives and scope of the research. Research background information is given in Chapter 2. Materials selection, grout composition, specimen construction, testing methods and procedures are discussed in Chapter 3. The preliminary mix design process is outlined in Chapter 4. This includes the preliminary aggregate testing, grout design and testing, and the results. The final mix designs that were based on the results of the preliminary testing are presented in Chapter 5. Chapter 6 presents the grout and compressive strength results of the final mix design testing. These results are then discussed and analyzed in Chapter 7. Chapter 8 provides conclusions and recommendations for further research.

2 BACKGROUND

2.1 General Literature Review

The following sections are comprised of summaries of the literature reviewed for this research.

Information about light-weight grout is extremely limited. There are very few research projects on light-weight grout, but there has been a lot of research done on light-weight concrete. This research using expanded shale will increase what is known about light-weight grout and determine the acceptability of using expanded shale in light-weight masonry grout. Testing has been done on light-weight concrete and some benefits of using light-weight material have been determined. Some of these benefits include lower in-place density, greater sound insulation, and better thermal insulating capacity than conventional concrete. These benefits are likely to be similar for light-weight grout.

2.1.1 Structural Light-weight Concrete

Regular use of light-weight concrete in multistory buildings and other large structures dates back to the 1950s [20]. The primary purpose in using light-weight concrete is to reduce the dead load of a concrete structure. This then allows load bearing elements such as columns and footings to be reduced. Many times, the marginally higher cost of light-weight concrete is offset by size reduction of structural elements and less reinforcing steel [22]. Light-weight aggregate concrete is about 28 percent lighter than normal concrete. This reduction in weight allows for great savings in column and footing sizes [16]. There are also other studies that report that this reduction in dead weight could result in a decrease in steel reinforcement as well [26]. This reduction in steel reinforcement can be seen in footing and columns as well, but also throughout the walls of the building. Since the dead load of the building is decreased, the seismic load on the building is decreased and this permits that less reinforcement can be used.

Light-weight structures also are known to have greater long-term durability. Light-weight aggregate concrete has a reduced likelihood of shrinkage, lower permeability, and generally a better bond between the cement paste and the aggregate [16]. Structural light-weight concrete also provides higher R-values which provides improved thermal insulation [22]. The thermal resistance of light-weight aggregate concrete is up to six times that of normal weight concrete [16]. Unal, Uygunoglu, and Yildiz investigated the thermal properties of light-weight concrete. Using sedimentary rock known as diatomite as the light-weight aggregate, they determined that there is a negative correlation between the unit weight and the thermal conductivity of the concrete [24]. Thermal conductivity varies inversely with the density of the material, so the light-weight material means a higher insulation value. This would be likely to apply to other light-weight material concrete.

Light-weight aggregate concrete provides greater sound insulation. The characteristics due to the air voids of the light-weight aggregate allows for better sound insulation [26]. These benefits of reduced dead loads, improved thermal insulation, and greater sound insulation for light-weight concrete will likely be found when light-weight material is used in masonry applications.

There is no precedent for using light-weight aggregate in masonry grout and very little research has been done on the topic. However, light-weight material has been used in other masonry applications such masonry units and mortar. Expanded shale is commonly used as light-weight material in structural elements [15]. Masonry units made with pumice aggregate have been tested and loaded with in-plane forces. That study determined that pumice can be used as an alternative to expanded shale in light-weight masonry units because they have similar properties and strength results [15].

2.1.2 Relevant Requirements for Grout and Masonry

The models used in the US *Building Code Requirements and Specification for Masonry Structures* rely on compressive strength values for design of masonry elements and structures [14]. The compressive strength of masonry, as a result of the prism test method, must either exceed or be equal to 10.3 MPa (1500 psi) but be no greater than 27.6 MPa (4000 psi) for concrete masonry in order to be used as a nominal strength value [14]. ASTM C476 standard specifics that grout for masonry must obtain a minimum compressive strength of 13.8 MPa (2000 psi) at 28 days [10] while the masonry code indicates that the specified compressive strength of grout shall exceed or be equal to the compressive strength of masonry while not exceeding 34.5 MPa (5000 psi) [14]. Curing ages at which strength must be achieved for grouts and masonry systems are not specified in the masonry code and 28-day strength references can only be found in the code's commentary. Masonry grout is also governed by more than just compressive strength. ASTM C476 also requires grout to have a slump between 200 to 280 mm (8 to 11 inches) and specifies aggregate and cement portions by volume when the proportion method is used [10].

2.2 Related Work

Petty and Nelson studied the use of blast furnace steel slag to produce structural masonry grout. In that study, four masonry grout types were tested with different percentages of Portland cement and aggregate; the article however does not disclose if these percentages were based on weight or volume. The values given are therefore assumed to be based on volume since that is what the standard proportions in ASTM C476 specify [10]. Petty and Nelson state that the light-weight grout is 31% Portland cement and 69% light-weight aggregate, while the normal-weight grout is 15% Portland cement and 85% normal-weight aggregate [22]. The first part of testing included testing the grout in an 8 foot wall so that the ease of installation and visual performance of the materials could be evaluated. The second part of testing was independent lab testing where the grout was tested according to ASTM C1019 [12]. Some of the results of the Petty and Nelson study are summarized in Table 1.

Table 1. Petty and Nelson Blast Furnace Steel Slag Results

Grout Type	Slump [mm (in)]	Unit Weight [g/cm^3 (pcf)]	28-day Compressive Strength [MPa (psi)]
NW Fine	279 (11.0)	2.21 (138.0)	25.7 (3727)
NW Coarse	267 (10.5)	2.36 (147.4)	22.6 (3285)
LW Fine	279 (11.0)	1.95 (121.6)	50.9 (7377)
LW Coarse	279 (11.0)	1.82 (113.4)	51.3 (7447)

Petty and Nelson determined that the required 28-day compressive strength of 13.8 MPa (2000 psi) was greatly exceeded by the light-weight grout samples. In fact, the light-weight grout made with blast furnace steel slag had significantly higher compressive strength than that of the normal-weight grout. The higher compressive strength of the light-weight grout was attributed to "higher cement contents" which were necessary to "properly coat the rough and porous surface of the light-weight aggregate" [22]. Even though light-weight grout is expected to need more cement to reach equivalent normal-weight compressive strengths, there is not enough information about the proportions to compare values to this expanded shale study. Light-weight grout can essentially be made to be as strong as desired by increasing the cement content.

3 TEST PROCEDURE

3.1 Overview

The following sections include information describing the selection, testing, and use of materials in regards to the manufacturing of grout.

3.2 Materials Selection

Material selection was based on ASTM standards. Type I/II Portland cement was used and all water was from a potable source. Two aggregate materials were used in testing: normal-weight aggregate and light-weight aggregate. ASTM C404 (Standard Specification for Aggregates for Masonry Grout) specifies two grout types: fine and coarse grout [9]. ASTM C404 identifies the required aggregate gradation for fine and coarse masonry grout. Normal-weight aggregate was provided by Geneva Rock and light-weight aggregate was provided by Utelite Corporation. Utelite material is designed to be used in structural concrete and therefore follows the ASTM C330 specifications for light-weight aggregates for structural concrete [8]. Coarse aggregate and crushed fines material from Utelite Corporation were used for the coarse and fine grout, respectively. These were the two Utelite materials that best matched the grout aggregate specifications specified by ASTM C404 [9]. Figure 1 shows a close-up of expanded shale aggregate (left picture), the crushed fines (middle picture), and the coarse aggregate (right picture) used in this research. The close-up picture has been magnified 10 times and clearly shows the porous nature of the expanded shale. The paper clip in the pictures provides a size comparison for the different aggregate. Table 2 gives the standard grout gradation according to ASTM C404, the standard light-weight aggregate structural concrete gradation according to ASTM C330 and the actual gradation for the material used in this research [9, 8].

Figure 1. Expanded Shale Close-up (Left), Crushed Fines (Middle), Coarse (Right)

Table 2. Utelite Expanded Shale Gradation

Sieve Size		Coarse Material			Fine Material		
mm	No.	ASTM C404 Standard (%)	ASTM C330 Standard (%)	Coarse Actual (%)	ASTM C404 Standard (%)	ASTM C330 Standard (%)	Crushed Fines (%)
19 mm	3/4"	-	100	100	-	-	-
12.5 mm	1/2"	100	90 - 100	92.67	-	-	-
9.5 mm	3/8”	90-100	40 - 80	68.39	-	100	100
4.75 mm	4	20-55	0 - 20	10.83	100	85 - 100	100
2.36 mm	8	5-30	0 - 10	0.61	95-100	-	95.85
1.18 mm	16	0-10	-	-	70-100	40 - 80	59.55
600 µm	30	0-5	-	-	40-75	-	31.65
300 µm	50	-	-	-	20-40	10 - 35	17
150 µm	100	-	-	-	10-25	5 - 25	10.10
PAN	PAN	-	-	0.61	0-10	-	10.10

3.3 Aggregate Testing

Aggregate testing was done before each grout test was performed. Aggregate was separated from the supply and stored in buckets to control the water content. Then a sample from the buckets was taken for aggregate testing. The information recorded during aggregate testing was used to determine the absorption, moisture content and specific gravity of each sample.

Procedures for the specific gravity and absorption tests were performed in accordance with ASTM C127 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate) [2] and ASTM C128 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate) [3]. Figure 2 shows the aggregate soaking for 24 ±2 hours before testing. The aggregate shown in Figure 2 from left to right is normal-weight coarse, normal-weight fine, light-weight fine, light-weight coarse. Each aggregate sample that was soaked was split into two samples and tested. The results of the two tests were averaged and used for further calculations. The fine and coarse aggregates were first brought to saturated-surface dry (SSD) condition by using a hairdryer and towels, respectively. A glass pycnometer was used when testing the fine aggregate and a metal pycnometer was used when testing the coarse aggregate. The pycnometers were first filled with de-aired water and weighed. They were emptied, dried out, and a SSD aggregate sample was placed in each pycnometer before being weighed again. The pycnometers were refilled with de-aired water while the SSD aggregate remained. A vacuum pump was connected to the pycnometers to completely remove any air remaining in water, as shown in Figure 3 and Figure 4, and the final weight of the pycnometer was recorded.

Figure 2. Aggregate Soaking

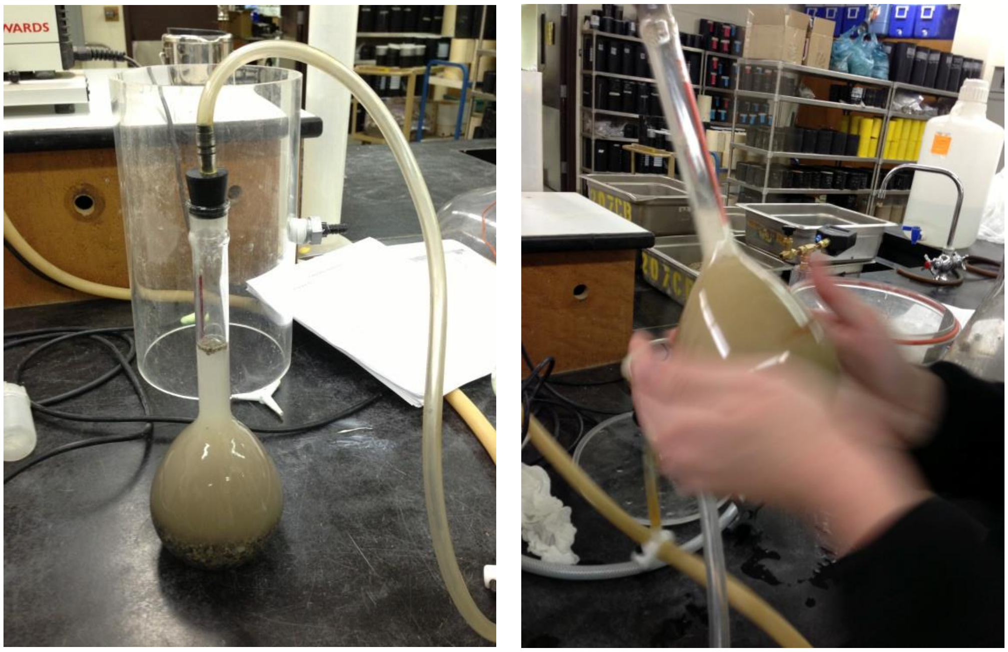

Figure 3. Fine Aggregate Testing with Vacuum Pump

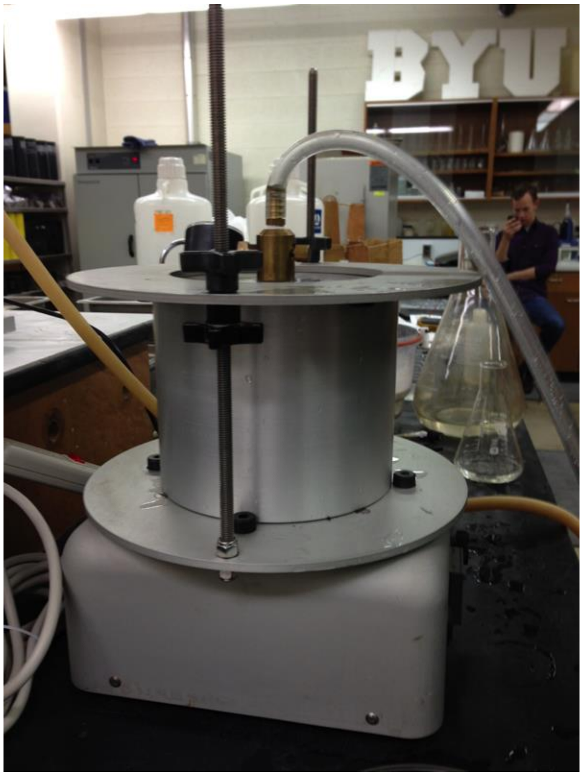

Figure 4. Coarse Aggregate Testing with Vacuum Pump

The values recorded during the aggregate testing were used to calculate the absorption, moisture content, and specific gravity of the aggregate. The absorption capacity (*A*) of the aggregate was calculated using Equation 3-1:

$$A = \left[\frac{W_{SSD} - W_{OD}}{W_{OD}}\right] \cdot 100 \qquad (3\text{-}1)$$

where WSSD and WOD represent the weight of the aggregate sample in the SSD and OD conditions, respectively. The moisture content (MC) of the aggregate was calculated using Equation 3-2:

$$MC = \left[\frac{W_E - W_{OD}}{W_{OD}}\right] \cdot 100 \qquad (3\text{-}2)$$

where W_E represents the weight of the aggregate sample in its existing conditions and W_{OD} represents the weight of the aggregate sample in its oven dry condition. The specific gravity (*SG*) of the aggregate was calculated using Equation 3-3:

$$SG = \frac{\left[\frac{W_{OD}}{(W_{pyc} - W{*}_{pyc} + W_{SSD})/(\gamma_{WT})}\right]}{\gamma_{w4^\circ C}} \qquad (3\text{-}3)$$

where W_{OD} is the weight of the OD aggregate sample and W_{SSD} is the weight of the SSD aggregate sample. W_{pyc} represents the weight of the pycnometer filled with de-aired water, and $W{*}_{pyc}$ represents the weight of the pycnometer filled with aggregate sample and de-aired water.

3.4 **Grout Composition and Testing**

The values from the aggregate testing were used to design grout mixtures and determine the w/c ratio, total volume, and total weight of each grout mixture. The grout was designed according to the cement and aggregate proportions specified in ASTM C476 [10]. These proportions are presented in Table 4.

Table 3. ASTM C476 Standard Grout Proportions

Type	Parts by Volume		
	Portland Cement	Fine Aggregate	Coarse Aggregate
Fine Grout	1	2.25-3	-
Coarse Grout	1	2.25-3	1-2

The aggregate and cement were weighed according to the mix design and mixed with a mechanical concrete mixer for about five minutes. Water was weighed before mixing began and was added incrementally until the desired slump was reached. Figure 5 shows the concrete mixer that was used with grout Type 3 inside. Since the w/c ratio was held constant between aggregate type grout, the slump was allowed to fluctuate.

Figure 5. Concrete Mechanical Mixer with Grout Type 3

Grout is required to have a slump of 8 to 11 in. (200 to 280 mm) according to ASTM C476 [10]. Slump tests were performed as outlined in ASTM C143 (Standard Test Method for Slump of Hydraulic-Cement Concrete) [5]. The standard slump cone was filled with three equal-volume lifts each consolidated by 25 strokes of the 5/8 in. diameter rod. After the top layer was rodded, the surface was struck off by screeding and rolling the tamping rod across the top. The mold was removed immediately in a vertical direction, eliminating any lateral or torsional motion, a distance of 12 in. in 5 ± 2 seconds [5]. Figure 6 shows the rodding process and the apparatus used for slump testing. Figure 7 demonstrates the slump measurement.

Figure 6. Slump Cone with Grout Type 6

Figure 7. Grout Slump Measurement with Grout Type 3

The component temperature of the grout was determined by inserting a glass thermometer into the grout in the center of the concrete mixing drum. The thermometer was allowed not to come in contact with the edge of the drum, so that this would not influence the temperature reading. The unit weight of the grout mixture was measured by following ASTM C138 (Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete) [4]. The weight of a clean and dry unit weight bucket with a volume of 0.1 ft^3 was recorded. The unit weight bucket was filled with grout in three equal volume lifts each consolidated by 25 strokes of the 5/8 in. diameter rod. Ten to 15 strikes of the rubber mallet were applied to the side of the bucket after placement of each lift. The excess grout was struck off using a strike-off plate, the sides of the bucket were cleaned off, and the full bucket was weighed [4]. The grout used in the unit weight test was added back into the drum and remixed. Figure 8 illustrates a full unit weight bucket.

Figure 8. Unit Weight Bucket with Grout.

An air test was performed by following ASTM C231 (Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method) [7]. The interior of the air-meter bowl was dampened and filled with grout in three equal volume lifts each consolidated by 25 strokes of the 5/8 in. diameter rod. Ten to 15 strikes of the rubber mallet were applied to the side of the bucket after placement of each lift. The excess grout was struck off of the top of the air-meter bowl using the strike plate. The rims of the bowl were cleaned off and the apparatus was assembled. The air valve between the air chamber and the measuring bowl was closed. Both petcocks on the holes through the cover were opened and filled with water, using a squirt bottle, until water emerged from the opposite petcock. The petcocks were closed and air was pumped into the air chamber until the gauge hand was on the initial pressure line. The gauge hand was stabilized at the initial pressure line by pumping or bleeding off air as necessary by tapping the gauge lightly by hand. The air valve between the air chamber and the air-meter bowl was opened and the side of the bowl was immediately struck with the mallet. After, the pressure gauge was lightly tapped by the hand to stabilize the gauge and the percentage of air on the dial of the pressure gauge was read off and recorded. The pressure was released by opening both petcocks before removing the cover and the grout material was discarded [7]. Figure 9 shows the apparatus used to determine the air content by the pressure method.

Figure 9. Air Content by the Pressure Method

Although segregation is not a standard test for grout, the grout being tested has the potential for segregation since light-weight aggregate is being used. Petty and Nelson used a visual approach to determine segregation of the light-weight grout, which they concluded did not occur. Instead of a visual approach, in the research presented herein, segregation was quantitatively measured using ASTM C1610 (Standard Test Method for Static Segregation of Self-Consolidating concrete Using Column Technique) [13]. The test method is a laboratory procedure to determine the potential static segregation. Although grout is not the same as self-consolidating concrete, the quantitative approach of ASTM C1610 is better than a qualitative visual approach.

In the static segregation test method, the segregation column mold was placed on flat, level ground and the column was filled completely with coarse grout within two minutes of remixing. The mold was filled above the rim and the top was struck off the by sliding the strike-off bar across the top rim of the mold with a sawing motion. The grout was then allowed to stand for 15 ± 1 min. Following the standing period, the metal plates were inserted between the top, middle and bottom sections. The top section was removed and washed through a No. 4 sieve so that only coarse aggregate remained on the sieve. This aggregate was placed in a clean pan. The middle section was removed and the grout was discarded. The bottom section was also washed through a No. 4 sieve and the aggregate was placed in a second clean pan. The coarse aggregate obtained from the top and bottom sections were brought to surface-dry condition by rolling them in an absorbent towel. The mass of surface-dry aggregate from both the bottom and top sections was recorded. These values were then used to calculate static segregation (S) with Equation 3-4:

$$S = \left[\frac{CA_B - CA_T}{CA_B + CA_T}\right] * 100 \qquad (3\text{-}4)$$

where CA_B is the mass of coarse aggregate in the top section of the column and CA_B is the mass of the coarse aggregate in the bottom section of the column. These values were used to calculate the static segregation by dividing the difference between the bottom and top sections by the average weight [13]. The segregation column is shown in Figure 10.

Figure 10. Segregation Column with Grout Type 5

3.5 **Grout Specimens and Testing**

After grout mixture testing was complete, four grout cylinder specimens were made for each grout type according to ASTM C192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory) [6]. Grout specimens should be made according to ASTM C1019 [12]. However, since this is a comparative study, the extra effort in preparing the grout molds following ASTM C1019 [12] standards was deemed unnecessary and plastic cylinders were used instead. Grout specimens were made for each batch by placing grout mixture in 4 in.

diameter plastic molds each 8 in. height that had release oil applied to the interiors. The grout was placed in each mold in two equal volume lifts each consolidated by 25 strokes of the 3/8 in. diameter rod. Ten to 15 strikes of the rubber mallet were applied to the side of the mold after placement of each lift. The top surface was struck off using the tamping rod. Lids were put on the cylinders and they were allowed to cure at room temperature for 24-hours [6]. Figure 11 shows grout Type 1 specimens before lids were placed on each cylinder. After 24 hours of curing, these specimens were removed from their molds and stored in a fog room for 28 days. On the day of testing, the specimens were removed from the fog room and allowed to acclimate before being capped with sulfur according to ASTM C617 (Standard Practice for Capping Cylindrical Concrete Specimens) [11]. Grout Type 5 cylinders that have been removed from the fog room and allowed to acclimate are presented in Figure 12.

Figure 11. Grout Type 1 Cylinder Specimens

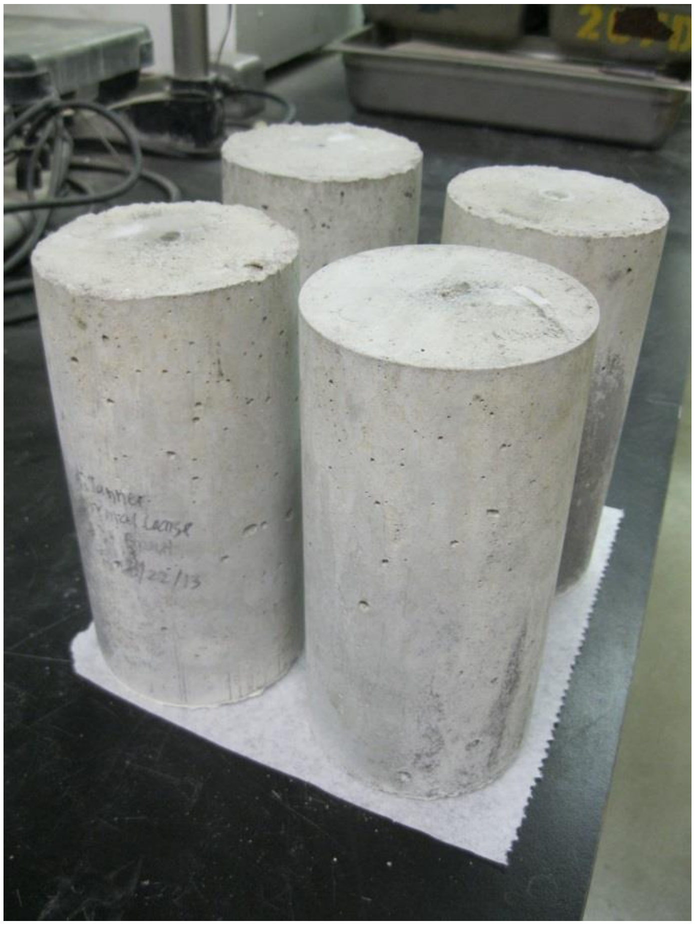

Figure 12. Grout Type 5 Cylinder Specimens

Compression testing was executed as indicated in ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) [1]. The required strain rate of 0.05-in./minute was applied using a floating base and the maximum load sustained by each specimen was recorded. A specimen in the compression testing apparatus is shown in Figure 13. After specimens reached failure, the paste-aggregate bonds and fracture pattern were noted and classified according to ASTM C39 [1]. Figure 14 illustrates the fracture patterns according to ASTM C39 [1].

Figure 13. Grout Specimen Compressive Testing

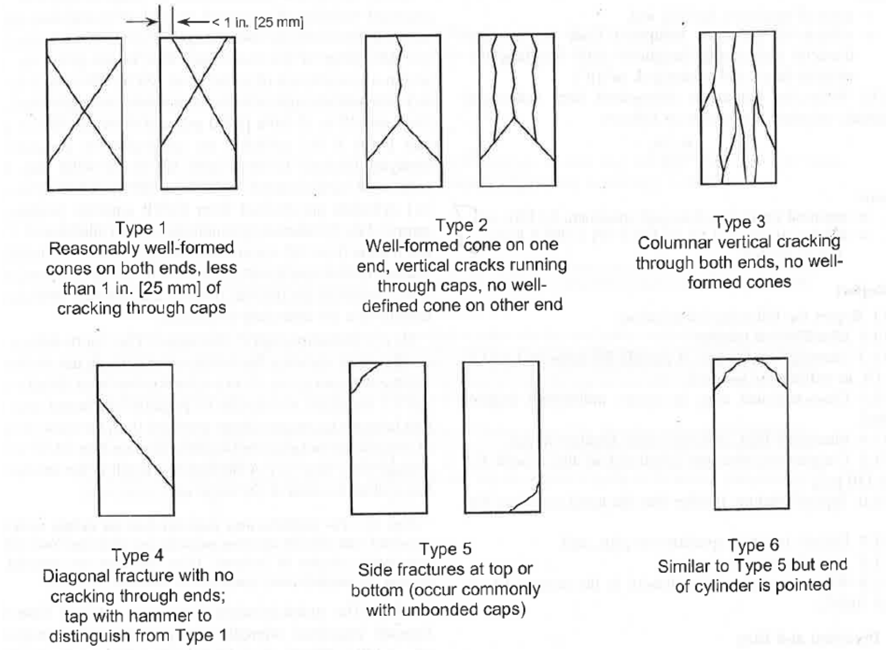

Figure 14. ASTM C39 Typical Fracture Patterns

4 PRELIMINARY MIX DESIGN

4.1 Overview

Preliminary testing was performed in order to determine if expanded shale light-weight grout was going to meet the necessary 28-day ASTM compressive strength standard of 13.8 MPa (2000 psi). This preliminary testing also helped determine what testing would best allow for strength comparisons between light-weight and normal-weight grout and which variables should be controlled.

4.2 Aggregate Testing

Aggregate testing was performed according to the process described in Section 3.3. Equations 3-1, 3-2, and 3-3 were used to calculate the absorption, moisture content and specific gravity for each aggregate. The results of these calculations are shown in Table 4.

Table 4. Absorption, Moisture Content, and Specific Gravity for Preliminary Testing

Aggregate #	Type	Grout Type #	Average Absorption (%)	Moisture Content (%)	Average Specific Gravity
P1	LWF	A	14.05	1.06	1.80
P2	NF	B	1.84	0.72	2.57
P3	LWF	C	19.97	6.360	1.88
P4	LWC	C	13.60	0.15	1.73
P5	LWF	D	17.48	4.18	1.88
P6	LWC	D	13.72	0.13	1.74

During some of the preliminary aggregate testing, it was observed that the absorption values for the light-weight aggregate differed depending on how long it was allowed to soak. We can see this difference between Aggregate P1, P3 and P5 because they were allowed to soak for different amounts of time. The ideal time to allow the aggregate to soak would be representative of how much water will be absorbed in the mixing process of the grout. Since much more testing would need to be done in order to determine this, the 24 hour ASTM C128 standard soaking time was used for all aggregate.

4.3 Grout Mix Design and Testing

The results from the aggregate testing were then used to design grout mixtures. The proportions of aggregate to cement by volume are shown in Table 5. These proportions do not align with the standards set forth in ASTM C476 because they were accidentally proportioned according to weight instead of volume. This meant that there was more aggregate present in each batch than there should have been. Although these preliminary grout tests did not meet the necessary proportion standards, they still provided useful information that contributed to designing the final grout batches.

Table 5. Grout Identification and Proportions for Preliminary Testing

Grout Type #	Grout Type	Aggregate Type	Proportions	
			Fine Agg.	Coarse Agg.
A	Fine	Light-weight	4.934	-
B	Fine	Normal-weight	5.045	-
C	Coarse	Light-weight	4.672	3.086
D	Coarse	Light-weight	4.742	3.072

Since these were preliminary tests, the grout was not designed according to a target w/c ratio or cement content. The grout was design to give a sufficient volume of grout to perform the necessary grout testing and create four cylinder specimens. The weight of the cement and aggregate were weighed out based on the grout design. Water was then added until a necessary slump of 200 to 280 m (8 and 11 inches) was reached and this amount of water was recorded.

Table 6 and Table 7 outline the grout design for grout Type C. The batched weights of all the materials are recorded in Table 6 along with the water content of the aggregate. These values, along with the absorption values, allowed for the equivalent SSD weight of the aggregate (EW_{SSD}) to be calculated with Equation 4-1:

$$EW_{SSD} = \frac{W_{BA} \cdot \left(1+\frac{A}{100}\right)}{\left(1+\frac{WC}{100}\right)} \tag{4-1}$$

where W_{BA} is the batched weight of the aggregate that is weighed out for the grout mixture construction, A is the absorption of the aggregate, and WC is the water content of the aggregate. Once the SSD equivalent weights for the aggregate are known, the free water weight can be calculated. Free water is the water that is available to react with the cement after accounting for the existing water in the aggregate and the water that is absorbed by the aggregate. The free water (FW) is given by:

$$FW = W_{BW} - (EW_{SSDC} - W_{BC}) - (EW_{SSDF} - W_{BF}) \tag{4-2}$$

where W_{BW} is the batched water weight, EW_{SSDC} is the equivalent SSD weight of the coarse aggregate, W_{BC} is the batched weight of the coarse aggregate, EW_{SSDF} is the equivalent SSD weight of the fine aggregate, and W_{BF} is the batched weight of the fine aggregate.

The volume of each material can be calculated with the specific gravities of the material. The equation for volume (V) is:

$$V = \frac{EW}{SG * \rho_w} \tag{4-3}$$

where EW is the equivalent weight of aggregate, batched weight of cement, or free water weight depending on which volume is being calculated; SG is the specific gravity of the material and ρ_w is the density of water, 1000 kg/m^3 (62.4 lb/ft^3). These calculations are summarized in Table 6 and Table 7. Appendix A includes similar tables for each preliminary and final grout mix design. A total of four preliminary mixes were tried before the final six mixes could be appropriately designed.

Table 6. Grout Type C LWC Weights

Ingredient		Batched Weight (lb)
Water		30.787
Cement		24.025
Coarse Aggregate		35.8
Water Content:	%	0.15
Fine Aggregate		59.4
Water Content:	%	6.36

Table 7. Grout Type C LWC Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		18.376	1.00	0.294
Cement		24.025	3.15	0.122
Coarse Aggregate (SSD)		40.607	1.73	0.377
Absorption:	%	13.6	-	-
Fine Aggregate (SSD)		67.003	1.88	0.571
Absorption:	%	20.0	-	-
Total		150.011	-	1.365

The w/c ratio and cement content could then be calculated from the recorded weights. The results of the grout testing done for each preliminary grout type are shown in Table 8 and Table 9.

Table 8. Grout Mixture Test Results for Preliminary Testing

Grout Type #	Slump [mm(in)]	Component Temperature [°C (°F)]	Measured Unit Weight [g/cm^3 (pcf)]	Measured Air Content (%)	Computed Air Content (%)
A	9.00	-	1.79 (111.9)	4.5	-0.83
B	9.00	26 (78)	2.20 (137.39)	3.6	-1.06
C	8.25	24 (76)	1.72 (107.16)	6.1	2.50
D	8.25	23 (74)	1.72 (107.36)	3.8	2.29

Table 9. Grout Mixture and Specimen Results for Preliminary Testing

Grout Type #	Grout Type	Aggregate Type	Cement Content [kg/m^3 (lb/yd^3)]	w/c ratio	Average Compression Strength [MPa (psi)]
A	Fine	LW	406 (685)	0.60	24.2 (3516)
B	Fine	NW	372 (627)	0.80	22.6 (3272)
C	Coarse	LW	275 (463)	0.76	19.1 (2775)
D	Coarse	LW	273 (460)	0.78	15.1 (2187)

After each cylinder was capped and tested in compression, the failure mode was classified according to the ASTM C39 fracture patterns shown in Figure 14. The strength of each preliminary grout cylinder and the fracture pattern classification is presented Table 10.

The results in Table 10 show that grout made with light-weight expanded shale reaches the necessary 28-day ASTM C476 compressive strength of 13.8 MPa (2000 psi). This meant that expanded shale aggregate proved to be an acceptable light-weight aggregate for grout. The purpose of the final mix designs was then to compare the strength of light-weight expanded shale aggregate grout and the strength normal-weight aggregate grout. This testing also led to the decision that in order to isolate the aggregate as the tested variable, the w/c ratio and the cement content would be held constant.

Table 10. Grout Compressive Strength and Fracture Pattern for Preliminary Testing

Grout Type	Specimen #	Compressive Strength [MPa (psi)]	Fracture Pattern
A	1	21.3 (3090)	4
	2	24.7 (3581)	2
	3	26.7 (3877)	2
	4	-	2
B	1	21.9 (3180)	2
	2	23.1 (3353)	2
	3	22.3 (3233)	4
	4	22.9 (3325)	1, 4
C	1	19.0 (2750)	1
	2	20.1 (2909)	1
	3	18.4 (2665)	2
	4	19.3 (2795)	4
D	1	14.8 (2147)	2
	2	14.2 (2055)	2, 4
	3	14.1 (2037)	2
	4	17.3 (2509)	-

5 FINAL MIX DESIGN

5.1 Overview

After the preliminary mix design and testing had been performed, six grout mixtures were designed to allow for optimal comparison. The preliminary trial mixes were crucial in the development of the final mixtures. The final mixtures were used for comparison of the compressive strength of normal-weight grout and light-weight grout made with expanded shale aggregate. The w/c ratio and cement content were kept constant to demonstrate this strength comparison. The cement content was increased in two of the grout mixes to determine the effect that this has on the strength of the light-weight grout.

5.2 Aggregate Testing

Aggregate testing for the final grout batches was performed according to the process described in Section 3.3 and all aggregate was soaked for 24 ±2 hours. The absorption, moisture content, and specific gravity results are presented in Table 11.

The absorption and moisture content for the light-weight aggregate varies between the fine and coarse material. The light-weight coarse grout was expected to have similar values to that of the fine material. This was not the case though; the absorption and moisture contents were lower for the coarse grout. Both materials were also tested for the preliminary grout mixtures and the results were consistent between the fine and coarse aggregate, independently. The difference in values may be attributed to size and porous nature of the light-weight aggregate.

Table 11. Aggregate Absorption, Moisture Content, and Specific Gravity Results

Aggregate #	Type	Grout Type #	Average Absorption (%)	Moisture Content (%)	Average Specific Gravity
1	NF	1	1.66	0.85	2.58
2	NF	4	1.61	1.20	2.59
3	NC	4	1.52	0.046	2.62
4	LWF	2	17.31	4.58	1.89
5	LWF	3	17.76	4.22	1.88
6	LWF	5, 6	18.31	3.91	1.87
7	LWC	5, 6	13.58	0.20	1.74

5.3 Grout Mix Design

Grout mixture designs were computed using the results from the aggregate testing. Normal-weight aggregate and light-weight aggregate were used to make standardized fine and coarse grout specified by ASTM C404 [9]. The quantities of cement and aggregate were proportioned by volume as specified by ASTM C476 [10]. These proportion standards are summarized in Table 3. The proportions for each grout type used in this study are presented in Table 12.

Table 12. Grout Identification and Proportions

Grout Type #	Grout Type	Aggregate Type	Proportions	
			Fine Agg.	Coarse Agg.
1	Fine	Normal-weight	3.071	-
2	Fine	Light-weight	3.070	-
3	Fine	Light-weight	2.407	-
4	Coarse	Normal-weight	3.025	1.816
5	Coarse	Light-weight	3.027	1.816
6	Coarse	Light-weight	2.334	1.401

Grout Type 1 and 4 with normal-weight aggregate were batched prior to the other grout types and the w/c ratio was determined for each type. The w/c ratio for grout Type 1 was held constant for the other fine grout types, while the w/c ratio for grout Type 4 was held constant for the other coarse grout types. The w/c ratios were held constant throughout, but the cement content was increased by approximately 30 percent by weight between grout Types 2 and 5 and grout Types 3 and 6.

Water was added incrementally to grout Type 1 and 4 to ensure that the standard grout slump of 200 to 280 mm (8 to 11 inches) was met. This value was recorded to determine the w/c ratio that was then targeted with the other grout types. Slump was allowed to fluctuate for the other grout types since water was added until the desired w/c ratio was reached.

6 RESULTS

6.1 Overview

Results of the grout and compression testing performed on the six grout types previously mentioned are presented in this chapter. Additional individual specimen results and figures are located in Appendix B.

6.2 Grout Mixture Results and Compressive Strength

Six variations of grout were tested to quantify their maximum compressive stress capacity. The slump, component temperature, unit weight, and air content were measured as part of the grout testing process. In addition to measuring the air content, the air content was calculated using the theoretical unit weight on an air free basis and the measured unit weight. The theoretical unit weight on an air free basis was calculated using Equation 6-1:

$$UW_T = \frac{TW}{TV} \tag{6-1}$$

where UW_T is the theoretical unit weight on an air free basis, TW is the total weight and TV is the total volume. The total weight and total volume are calculated using Equation 4-1, 4-2, and 4-3. The total weight and volume of the grout mixture were determined by the water content, absorption, and specific gravity of the aggregate used. The computed air content was calculated using Equation 6-2:

$$AC = \frac{UW_T - UW_M}{UW_T} * 100 \tag{6-2}$$

where AC is the computed air content of the grout and UW_M is the measured unit weight of the grout. The results for the grout testing are presented in Table 13.

Table 13. Grout Mixture Test Results

Grout Type #	Slump [mm (in)]	Component Temperature [°C (°F)]	Measured Unit Weight [g/cm^3 (pcf)]	Measured Air Content (%)	Computed Air Content (%)	Segregation (%)
1	254 (10.00)	22 (72)	2.25 (140.3)	2.4	-2.60	-
2	273 (10.75)	21 (70)	1.81 (112.9)	3.0	1.87	-
3	279 (11.00)	23 (73)	1.80 (112.3)	2.7	1.99	-
4	248 (9.75)	26 (79)	2.32 (144.6)	1.4	-1.98	6.4
5	260 (10.25)	22 (71)	1.79 (111.8)	3.0	3.34	7.7
6	279 (11.00)	22 (71)	1.71 (106.7)	3.0	4.14	7.0

The results of the final cement content, w/c ratio, and average compression strength of the four cylinders are presented in Table 14 for each grout type. The cement content (CC) was determined using Equation 6-3:

$$CC = \frac{W_C - UW_M}{W_{TOTAL}} \qquad (6\text{-}3)$$

where W_C is the weight of cement in the grout mixture, UW_M is the measured unit weight, and W_{TOTAL} is the total calculated weight of the grout mixture. The w/c ratio is the ratio between the free water weight and the cement weight in the grout mixture.

Table 14. Grout Mixture and Specimen Results

Grout Type #	Grout Type	Cement Content [kg/m^3 (lb/yd^3)]	w/c ratio	Average Compression Strength [MPa (psi)]
1	Fine	550 (927)	0.57	39.5 (5722)
2	Fine	533 (898)	0.55	24.5 (3550)
3	Fine	606 (1022)	0.53	22.0 (3189)
4	Coarse	413 (696)	0.62	34.4 (4984)
5	Coarse	394 (664)	0.60	19.1 (2763)
6	Coarse	454 (765)	0.61	24.7 (3578)

After each cylinder compressive strength test, the failure mode was observed and classified according to ASTM C39 standards shown in Figure 14. The compressive strength of each cylinder and its fracture pattern classification are displayed in Table 15.

Table 15. Grout Specimen Compressive Strength and Fracture Pattern

Grout Type	Specimen #	Compressive Strength [psi (MPa)]	Fracture Pattern
1	1	5846 (40.3)	1,4
	2	4857 (33.5)	2
	3	6153 (42.4)	2
	4	6034 (41.6)	1,4
2	1	3771 (26.0)	2
	2	3602 (24.8)	2
	3	3503 (24.2)	3
	4	3325 (22.9)	2
3	1	3108 (21.4)	3,4
	2	3511 (24.2)	3
	3	2905 (20.0)	3
	4	3233 (22.3)	3
4	1	4775 (23.9)	2
	2	5083 (35.0)	4
	3	4980 (34.3)	4
	4	5098 (35.15)	4
5	1	2797 (19.3)	2
	2	2857 (19.7)	2
	3	2744 (18.9)	3
	4	2652 (18.3)	2
6	1	3222 (22.2)	2
	2	3646 (25.1)	3
	3	3831 (26.4)	2
	4	3611 (24.9)	2

7 DISCUSSION

7.1 Overview

The results presented in Chapter 6 are discussed, compared, and analyzed in this chapter. The grout testing results have been examined as well the failure modes. The results of this study are compared to Petty and Nelson's study on using blast furnace steel slag as light-weight aggregate in masonry grout. The masonry code and ASTM standard requirements are also compared to the testing results.

7.2 Result Analysis

Relationships can be seen between some of the grout mixture results. Figure 15 shows the average compression strength of each grout type versus the corresponding measured air content and computed air content. Inconsistencies were observed between measured and computed air contents. Computed air contents for the fine and coarse normal-weight grout (grout Type 1 and 4) were negative values. Since grout cannot have a negative air content it would be assumed that there are experimental measurement or computation errors. The calculations have been thoroughly checked, so it is probable that the data used to compute the air content may not be accurate. The specific gravities determined for the fine and coarse normal-weight aggregate are most likely too low and are causing the negative air computation. Additional aggregate testing should be performed to determine the accuracy of the aggregate specific gravity.

Since the computed air content values are negative values for the normal-weight aggregate, these numbers cannot easily be analyzed. Looking at the remaining values for the computed air contents for light-weight aggregate, they do not appear to have a trend. This means that based on the light-weight computed air contents the air content of the grout is not directly related to the compressive strength. The measured air content does appear to show a negative correlation between the two values though. Since this is such a small sample size, more testing should be done to determine if there is an overall trend that can be seen between the compressive strength of grout and the measured or computed air content or if they are independent values.

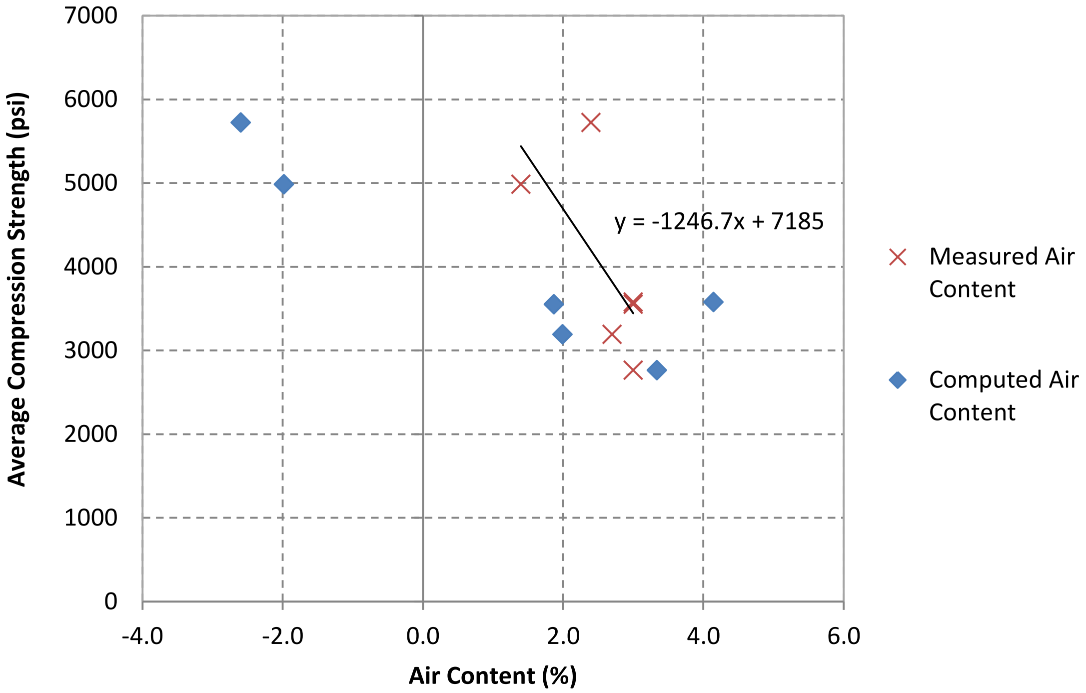

Figure 15. Average Compression Strength Versus Air Content

A similar relationship is seen in Figure 16 between the component temperature and the air content. According to Chauvenet's criterion to determine outlying data points, as outlined in Experimental Methods for Engineers, the 79°F data point is qualified as an outlier. The mean temperature value is 72.67°F with a standard deviation of 3.27°F. The maximum acceptable deviation to standard deviation ratio is 1.73 for *n* equal to 6. Since the deviation to standard deviation ratio for 79°F was 1.94 it was deemed as an outlier. The new mean, excluding this point, is 71.4°F with a standard deviation of 1.14°F. Since this means we do not consider the data for 79°F in Figure 16, it can be observed that the correlation between component temperature and air content do not correlate.

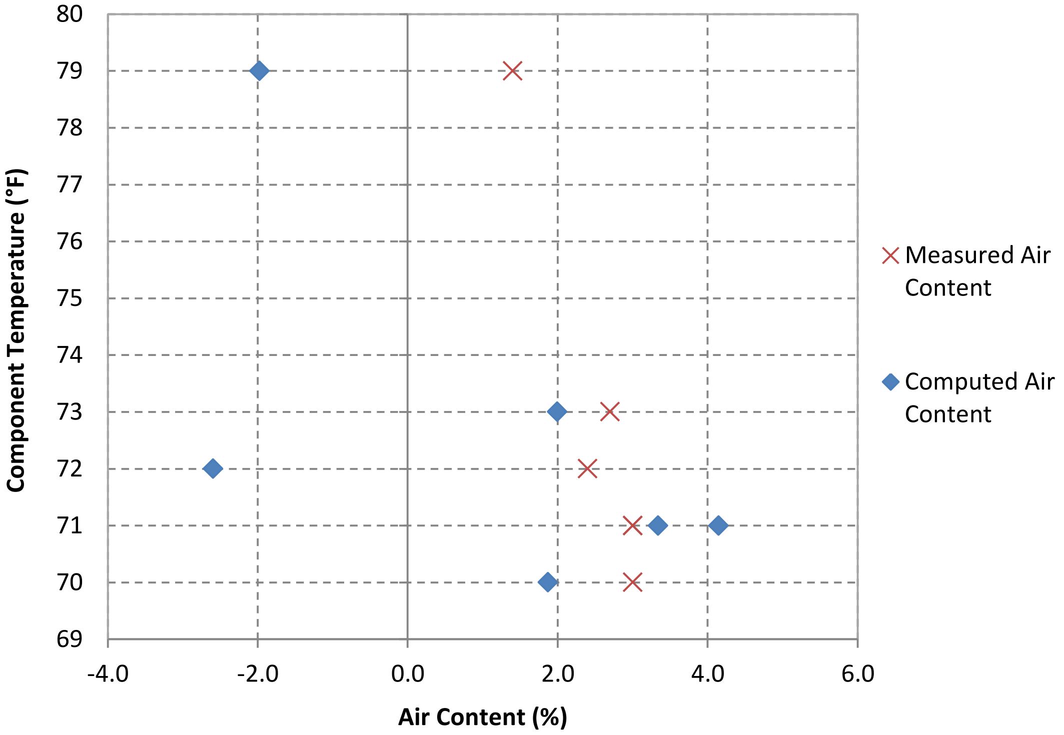

Figure 16. Temperature versus Air Content

The plot comparing component temperature versus slump is illustrated in Figure 17. The 79°F value would also be considered an outlier in this comparison. Comparing the remaining results there does not appear to be a strong correlation between the grout component temperature and the slump. More testing should be done to verify that these values are independent of one another.

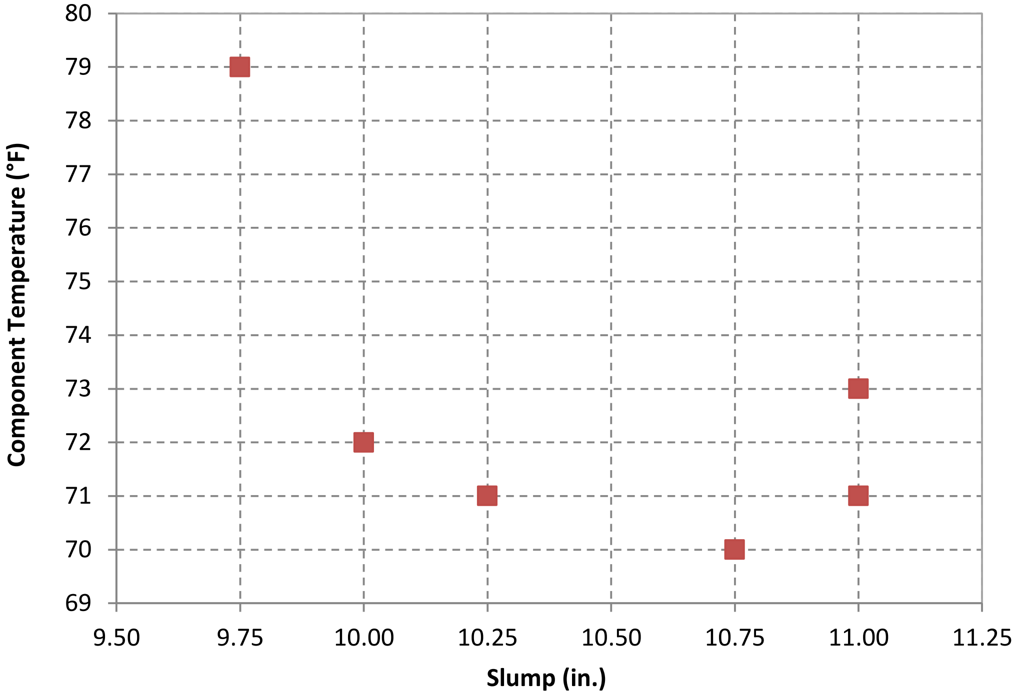

Figure 17. Temperature versus Slump

Figure 18 compares the average compression strength to the cement content with each data point labeled with the corresponding grout type. The hypothesis that an increase in cement content would correlate to an increase in compression strength was observed between the normal-weight grout types. These normal-weight grout types, Types 1 and 4, also differ in material; Type 1 being fine grout and Type 4 being coarse grout. The difference in aggregate material could also be a contributing factor to the difference in compressive strengths. Additional testing of both grout materials needs to be tested to verify correlation.

The increase in cement content from grout Type 5 to grout Type 6, while aiming to keep the w/c ratio constant, was expected to translate to an increase in the compressive strength for grout Type 6. The expected result materialized and the compressive strength of grout Type 6 was

24.7 MPa while that of grout Type 5 was 19.1 MPa. The increase in compressive strength was approximately 30 percent.

It was interesting to observe the unexpected result of grout Type 3. An increase in compressive strength from grout Type 2 to grout Type 3 was also expected, similar to the increase observed from grout Type 5 to grout Type 6. The increase, however, did not occur and the reason for this occurrence may be attributed to a few different things. Possible reasons for this result may be due to water evaporating from grout Type 2 before the cylinders were cast (decreasing the w/c ratio and increasing the compressive strength) or grout Type 3 not being thoroughly mixed (unmixed Portland cement would not contribute to the gain in strength). There is also a possibility that a measurement error occurred. Another option is a possible cement content theory. Increasing the cement content of a material will increase the strength of the bond between aggregate and cement paste but at a certain point the aggregate will become weaker than that bond. At this point, more cement may not strengthen the aggregate-cement matrix because the aggregate is now the weak point. Additional cement could strengthen the cement paste itself though, but will likely reach a point where compressive strength is maxed out and adding more cement will not increase the compressive strength. The difference in strength increase between Type 5 and 6 and the strength decrease between Type 2 and 3 cannot be attributed to one of these theories for certain. The definite cause of this anomaly is unsure and further testing is required to either validate or refute the findings which have been presented. A correlation cannot be determined from Figure 18 because more than two points are necessary to determine a correlation between cement content and strength for fine grout and that for coarse grout.

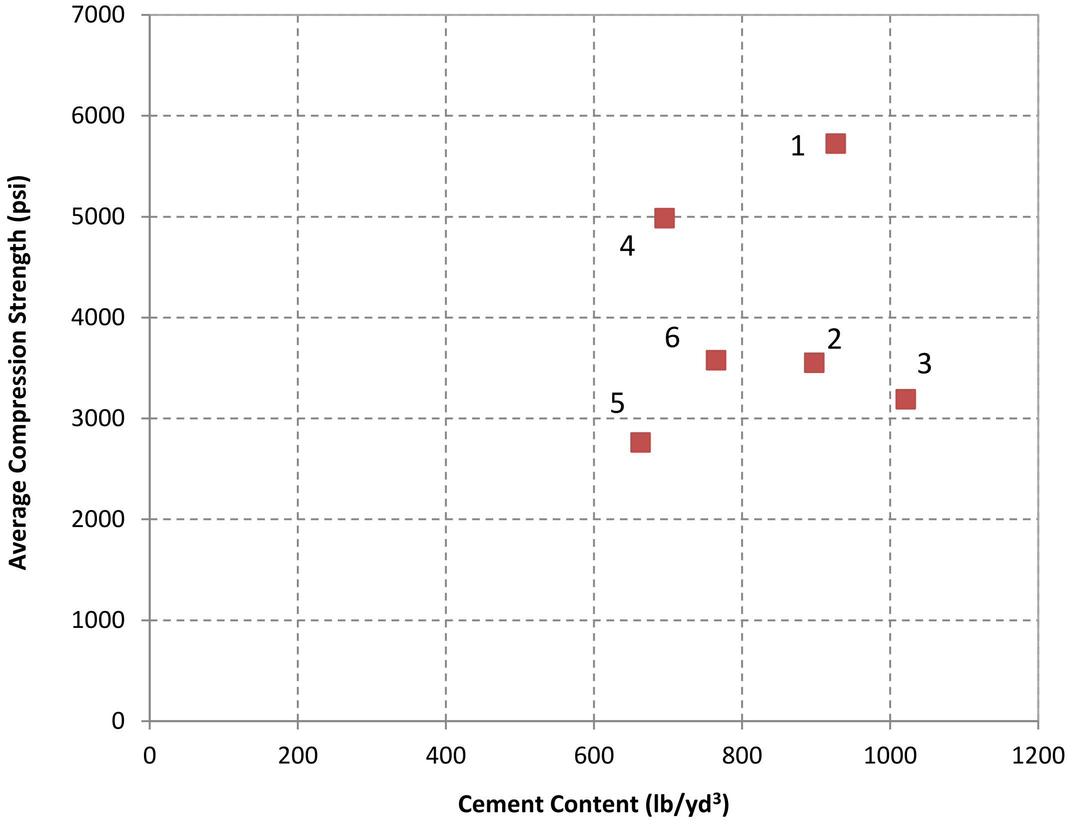

Figure 18. Average Compression Strength versus Cement Content

The relationship between average compressive strength and w/c ratio for each grout type is shown in Figure 19. An increase in w/c ratio typically correlates to a decrease in compressive strength. Common aggregate material data points should be compared in this figure since different aggregate types may influence the compressive strength differently. Comparing grout Type 2 and 3 and comparing grout Type 5 and 6 illustrates that an increase in w/c ratio actually leads to an increase in compressive strength. Since there are only two data points for each aggregate type, there is not enough data to define a definite correlation. More tests should be performed before any possible correlation between average compressive strength and w/c ratio can be determined.

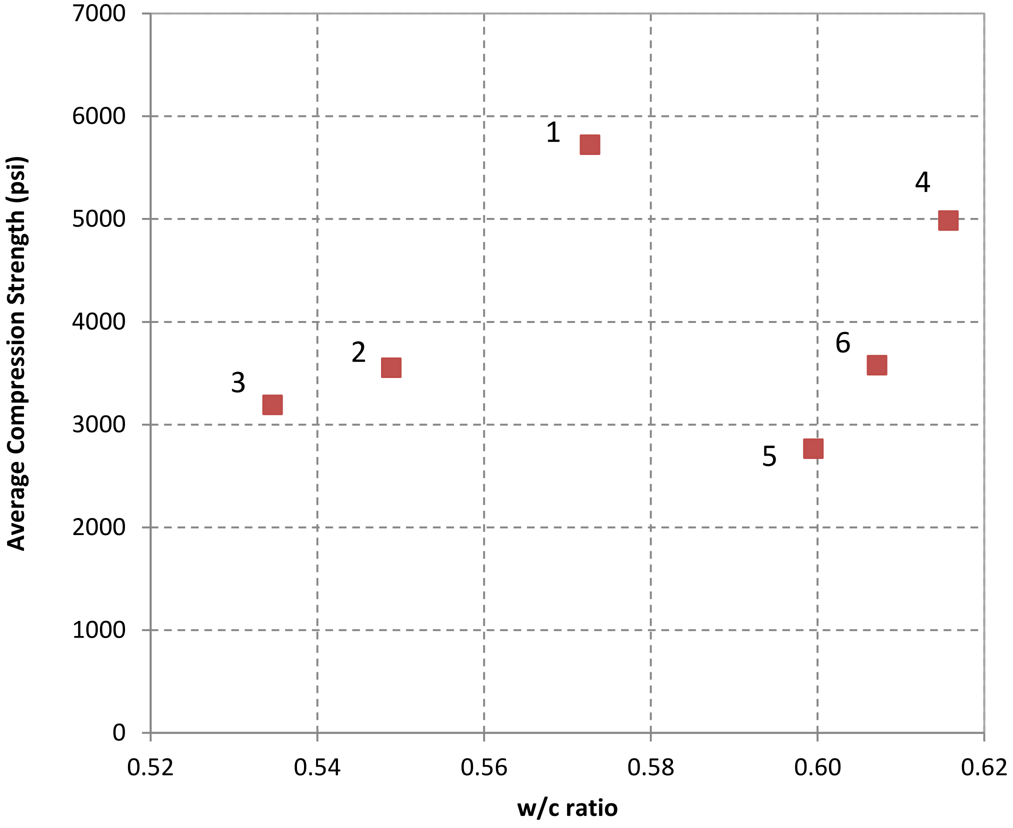

Figure 19. Average Compression Strength versus w/c Ratio

It should be noted that only one batch of each grout type design was made and there were four cylinders made for each grout type. Since this is a small sample size, the statistical significance of these values cannot be accurately calculated and represented.

7.3 Segregation Analysis

Segregation was tested according to ASTM C1610 [13] for coarse grout Types 4, 5, and 6. Only the coarse grout types were tested for segregation since the grout retained in the top and bottom sections was washed over a 4.5 mm (No. 4) sieve. The static segregation was calculated using Equation 3-4 and the results for these tests are presented in Table 13. Grout Type 4, 5 and

6 had static segregation values of 6.4, 7.7, and 7.0 percent, respectively. According to ACI 237R-07, a self-consolidating concrete mixture is generally considered to be acceptable if the percent segregation is less than 10 percent [14]. The lower the segregation value, the less likely the grout is to segregate. Using ACI 237R-07 as a guideline, the potential for static segregation of grouts 4, 5, and 6 is acceptable and significant segregation of greater than 10 percent is not likely to occur.

7.4 **Failure Mode Analysis**

Each cylinder specimen was observed after compressive strength testing was completed. The fracture pattern was classified and these results are given in Table 15. The failure planes were also observed to see how the aggregate-cement matrix fractured. Figure 20 shows a normal-weight coarse grout cylinder (top picture) and a light-weight coarse grout cylinder (bottom picture) after compression testing. Both types of grout failed in a well-formed cone pattern with vertical cracks through the cap with a cone on the other side. The cracks on the normal-weight coarse grout specimens were mostly around the aggregate instead of through the aggregate. This indicates that the weakness in these specimens was the matrix and the cement-aggregate bond instead of the aggregate itself. The cracks on the light-weight coarse grout specimens, however, went through the aggregate, meaning that the aggregate was the “weak link” of the system. Figure 21 shows a normal-weight fine grout cylinder (top picture) and a light-weight fine grout cylinder (bottom picture) after they have been tested. The normal-weight fine grout failed in a well-formed cone pattern, similar to the failure observed for the coarse grouts. The light-weight fine grout, however, failed with columnar vertical cracking with a small cone at the base. The fine aggregate is too small to view if the cracking was through or around the aggregate. Further testing and observations with a microscope should be performed in order to determine if the fine grout breaks similar to the coarse.

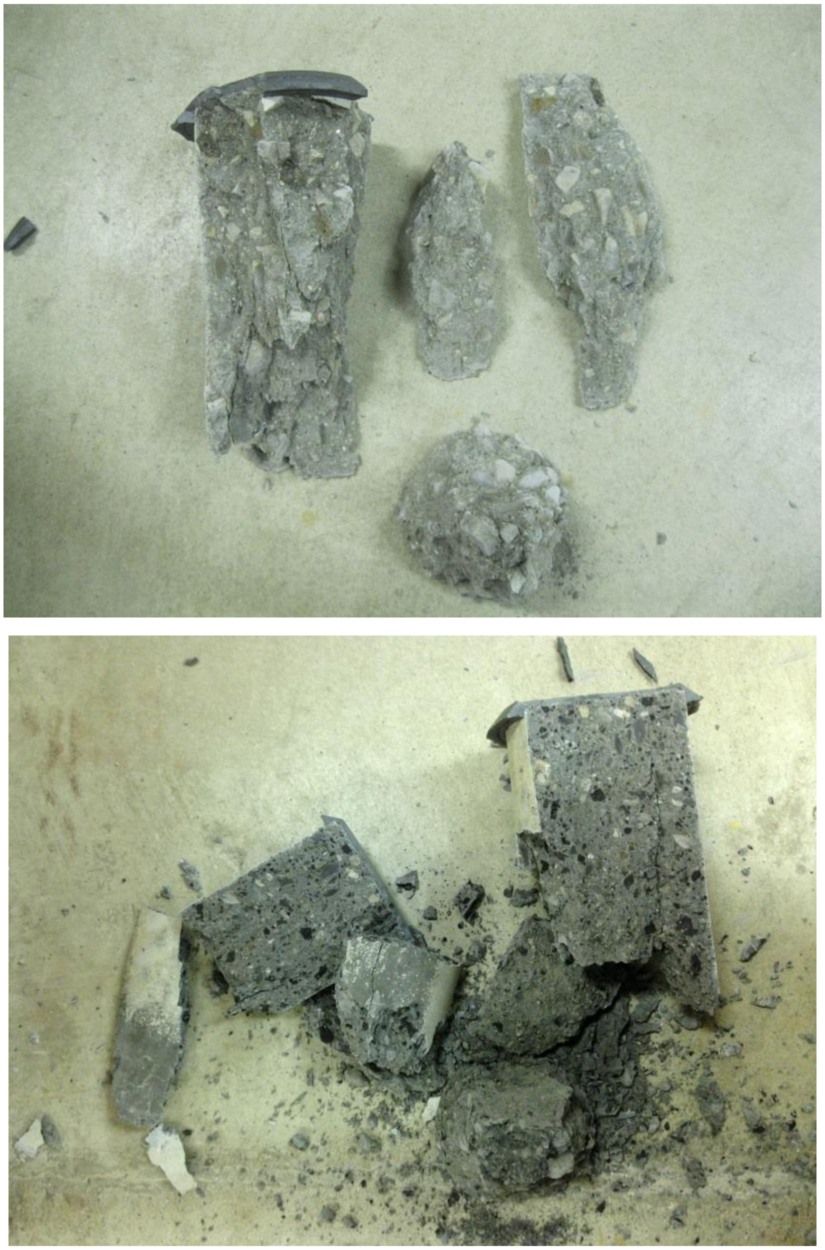

Figure 20. Normal-Weight Coarse Grout Failure and Light-Weight Coarse Grout Failure

Figure 21. Normal-Weight Fine Grout Failure and Light-Weight Fine Grout Failure

7.5 Petty and Nelson [23] Comparison

Direct comparison of compressive strength results between Petty and Nelson’s blast furnace steel slag study and the results from the expanded shale testing cannot be directly compared because of the difference in grout mixture design. The same variables have not been controlled between the two studies and Petty and Nelson do not specify the cement content or w/c ratio of for their grout types. They did include the proportions of cement and aggregate by percentage, as well as the water addition rate for each grout type given in percentage by weight of the total mixture. The U.S. Department of Transportation Federal Highway Administration (FHWA) states that the specific gravity for blast furnace slag is 2.0-2.5 and the absorption is 1-6 percent [19]. The moisture content of the blast furnace slag used in Perry and Nelson's study is unknown and values have been assumed. The average moisture content values of the blast furnace slag aggregate were assumed to be the same as the moisture content of the expanded shale. The values for absorption, specific gravity, and moisture content for blast furnace slag were all assumed to be the same as those for the normal-weight aggregate presented in this expanded shale study. The cement content was back calculated for each grout type using the FHWA blast furnace slag standard values, the given proportions, the water addition rates, the unit weights, and the other stated assumptions. These calculations are similar to those presented in Equation 4-1, 4-2, and 4-3. The cement content results for Petty and Nelson's study are shown in Table 16. The ratio between compressive strength and cement content will be used to compare blast furnace slag grout and expanded shale grout mixtures.

Table 17 presents comparable values for the results of this research with expanded shale aggregate. All values except ninth column (compressive strength) are based off the assumed values given above. The compressive strength values in the ninth column are results given in Petty and Nelson's study [23]. Petty and Nelson did not include cement content results in their study. Therefore, the computed cement content based off of the previously stated assumed values cannot be directly compared to results from Petty and Nelson.

Table 16. Blast Furnace Steel Slag Result Comparison

	Absorption (%)		Specific Gravity		Moisture Content				
Grout Type	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.	Cement Content (C.C.) (lb/yd^3)	Compressive Strength (psi)	Compressive Strength/C.C.
LWC1	1.00	1.00	2.00	2.00	4.24	0.20	1002	7447	7.43
LWC2	1.00	1.00	2.50	2.50	4.24	0.20	873	7447	8.53
LWC3	6.00	6.00	2.00	2.00	4.24	0.20	1031	7447	7.23
LWC4	6.00	6.00	2.50	2.50	4.24	0.20	900	7447	8.27
LWF1	1.00	-	2.00	-	4.24	-	1103	7377	6.69
LWF2	1.00	-	2.50	-	4.24	-	961	7377	7.68
LWF3	6.00	-	2.00	-	4.24	-	1135	7377	6.50
LWF4	6.00	-	2.50	-	4.24	-	991	7377	7.45
NWC	1.63	1.52	2.58	2.62	1.03	0.05	487	3285	6.74
NWF	1.63	1.52	2.58	2.62	1.03	0.05	503	3727	7.40

Table 17. Expanded Shale Result Comparison

	Absorption (%)		Specific Gravity		Moisture Content				
Grout Type #	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.	Cement Content (C.C.) (lb/yd^3)	Compressive Strength (psi)	Compressive Strength/CC
1	1.66	-	2.58	-	0.85	-	927	5722	6.17
2	17.31	-	4.58	-	4.58	-	898	3550	3.95
3	17.76	-	4.22	-	4.22	-	1022	3189	3.12
4	1.61	1.52	2.59	2.62	1.20	0.05	696	4984	7.17
5	18.31	13.58	1.87	1.74	3.91	0.20	664	2763	4.16
6	18.31	13.58	1.87	1.74	3.91	0.20	765	3578	4.67

The compressive strength to cement content ratio of each light-weight aggregate grout was divided by the compressive strength to cement content ratio of each normal-weight aggregate grout. These ratios show the benefit of using light-weight aggregate instead of normal-weight aggregate. If the compressive strength to cement content ratio for light-weight aggregate is greater than that for normal-weight aggregate, then the light-weight aggregate is more efficient. The ratios for the blast furnace slag and the expanded shale are shown in Table 18.

Table 18. Steel Slag Ratio and Expanded Shale Ratio Comparison

Steel Slag Ratio (%)	
LWC1/NWC	10.24
LWC2/NWC	2 6.55
LWC3/NWC	7.17
LWC4/NWC	22.71
LWF1/NWF	-9.62
LWF2/NWF	3.74
LWF3/NWF	-12.18
LWF4/NWF	0.58

Expanded Shale Ratio (%)	
Type2/Type1	-35.97
Type3/Type1	-49.44
Type5/Type4	-41.90
Type6/Type4	-34.76

From these results it appears that blast furnace slag is a slightly better choice for light-weight aggregate. The expanded shale ratios are all negative because the ratios of compressive strength to cement content for the light-weight aggregate were not greater than those for normal-weight aggregate. This means that the normal-weight grout is actually a better grout based on just the compressive strength and cement content values. The necessary increase in cement content to reach comparable compressive strengths for expanded shale grout may not be worth the increased cost of aggregate and cement. The benefits of reduced dead loads, improved thermal insulation and improved sound insulation could potentially still influence the choice of material used in construction though. More testing should be done to verify the results of the ratios and the assumptions made about blast furnace slag.

7.6 **Result Standard Comparison**

The *Building Code Requirements and Specification for Masonry Structures* outlines the requirements for the specified compressive strengths of both grout and masonry. The code does not specific curing ages for strength development. The code commentary discusses a 28-day compressive strength and it is inferred that this is the strength referred to in the specifications due to the upper bound limitations. The code requires f'_m to either exceed or be equal to 10.3 MPa

(1500 psi) but be no greater than 27.6 MPa (4000 psi) and f'_g to exceed or be equal to that of f'_m [14]. The ASTM standard for grout requires a minimum strength of 13.8 MPa (2000 psi) at 28 days [10]. Since this is a comparative study, cylinder specimens were constructed instead of grout prisms. Therefore the grout compressive strengths are not compared to the compressive strength of masonry, but are deemed adequate solely by the ASTM standards. Grout prism testing would result in the masonry absorbing some of the water in the grout. This decrease in the w/c ratio would be expected to increase the strength of the grout. Therefore the results of this study effectively determine if the expanded shale light-weight grout meets the necessary ASTM standards.

8 CONCLUSIONS

8.1 Summary

A testing program was devised involving testing light-weight and normal-weight aggregates to determine their properties and then designing, manufacturing, and testing light-weight and normal-weight grout variations. Light-weight masonry grout, constructed with expanded shale aggregate, was compared to normal-weight grout made with the same proportions by volume. The normal-weight and light-weight aggregate was tested prior to the grout batches to determine their absorption and existing water content. Preliminary aggregate and grout testing was performed in order to determine how expanded shale would behave. The information from this preliminary testing was used to design six grout batches: three were fine grout and three were coarse grout. The slump, component temperature, unit weight, and air content were measured as part of the grout testing process. The computed air content was also determined using the theoretical unit weight on an air-free basis and the measured unit weight.

Four cylinders were produced for each grout batch and allowed to cure for 28-days in a fog room. The cylinder specimens were sulfur capped and tested in compression. The cylinder specimens were also evaluated by reporting a failure mode and observing the fracture planes.

Comparisons and relationships between the grout testing results have been discussed. Evaluation of the Petty and Nelson study in relation to the research presented on expanded shale has been made. The results of the expanded shale grout testing have also been compared to the masonry code and ASTM standards and deemed acceptable.

8.2 **Findings**

Unlike the results obtained by Petty and Nelson, the compressive strength of the grout mixtures containing light-weight aggregate did not far surpass the compressive strength of the grout mixtures containing normal-weight aggregate. Petty and Nelson stated that “higher compressive strength values were expected for the light-weight materials because of their higher cement contents” [23]. The compressive strength results of the expanded shale testing cannot be directly compared to that from Petty and Nelson, but comparisons have been made between the ratio of compressive strength to cement content. After assuming some values and performing some back calculations, these ratios between light-weight and normal-weight grout can be compared to determine the benefit of using light-weight aggregate. From these results it appears that expanded shale aggregate does not prove beneficial, but that blast furnace slag aggregate can be beneficial. Grout testing with blast furnace slag aggregate was not performed in this study though and all results are based off of assumptions for blast furnace slag aggregate. Because assumptions have been made to make the comparison between blast furnace slag grout and expanded shale grout possible, more testing should be done to validate these relationships. Another difference that should also be studied is the possible difference in bond between Portland cement and blast furnace steel slag and that of Portland cement and expanded shale. This possible difference may contribute to the compressive strength differences between the studies.

The need for a higher cement content in expanded shale aggregate grout in order to obtain compressive strength values comparable to normal-weight aggregate grout was observed in the Petty and Nelson assessment. The necessary cement content to reach this comparable compressive strength is unknown. Further testing could be done to determine this value. The reason light-weight aggregate requires a higher cement content is most likely due to the shape and texture of expanded shale aggregate. Expanded shale is angular and porous, while normal-weight aggregate is typically rounder and smoother. More Portland cement is, therefore, needed to thoroughly coat the light-weight aggregate and would be a cost disadvantage.

All light-weight grouts in this study achieved the 28-day ASTM C476 compressive strength standard of 13.8 MPa (2000 psi) without increasing the standard Portland cement proportion [10]. It is important to note that the compressive strength values obtained in this study are for a comparative basis and are determined using cylinder specimens. These compressive strengths do not correspond to actual grout strength due to the water that has not been absorbed by the masonry units. It is assumed that the absorbed water would lower the w/c ratio of grout and consequently increase the grout compressive strength. Therefore, one can expect that expanded shale grout made with approximately the same amount of Portland cement as normal weight grout would reach the minimum compressive strength specified by the standards.

This research determined that light-weight grout made with expanded shale is adequate according to ASTM standards. The use of light-weight aggregate in concrete results in lower in-place density, greater sound insulation, and better thermal insulating capacity than conventional concrete [16, 22, 24, 26]. The use of light-weight grout may have many similar benefits. However, the use of light-weight aggregate in grout increases the cement demand and light-weight aggregate is also more expensive than normal-weight aggregate. These factors should be more closely evaluated to determine if light-weight grout is an economical decision.

8.3 Recommendations for Further Research

The obtained results are encouraging and further research should be performed to validate results and to expand the knowledge on expanded shale grout. Light-weight aggregate should also be used in masonry prism testing to ensure that the required masonry compressive strength is met.

A testing program comparing normal-weight grout, expanded shale grout, and blast furnace steel slag grout would be valuable in determining which grout type provides the best benefits. Being able to control the same values and have the same batch designs would allow for direct result comparisons that could not be accomplished with Petty and Nelson's study.

An observation of interest is that the fine grout made with expanded shale experienced a different mode of failure than that experienced by all other specimens. Fine grout made with expanded shale failed in a columnar vertical cracking manner while the other specimens failed in the typical conical manner. This observation needs further investigation to determine its effect on the behavior of masonry constructed with such type of grout.

A notable observation was made when increasing the Portland cement content for the fine grout made with expanded shale. Researchers expected an increase in compressive strength with increase in Portland cement content. This occurred for the light-weight coarse grout but not the light-weight fine grout. A few theories for the cause of this have been shared in Chapter 7. Testing should be repeated to determine the consistency of these results.

Segregation of the light-weight material may be a concern but currently there is no quantitative method to determine the segregation potential of grouts made with light-weight material. In the study presented herein, the static segregation of grout was determined using ASTM C1610 [8], which is the standard test method for static segregation of self-consolidating concrete, combined with the guidelines given by ACI 237R-07 [9]. The method and guidelines must be further verified.

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APPENDIX A. GROUT MIX DESIGN

The following tables are the batched weights and volumetric analysis for each grout type. The information regarding the preliminary grout tests is also included.

Table A-1: Grout Type 1 NWF (6/11/13) Weights

Ingredient		Batched Weight (lb)
Water		16.001
Cement		27.000
Coarse Aggregate		0
Water Content:	%	0
Fine Aggregate		67.4
Water Content:	%	0.85

Table A-2: Grout Type 1 NWF (6/11/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		15.464	1.00	0.248
Cement		27.000	3.15	0.137
Coarse Aggregate (SSD)		0	-	-
Absorption:	%	0	-	-
Fine Aggregate (SSD)		67.923	2.58	0.422
Absorption:	%	1.66	-	-
Total		110.387	-	0.807

Table A-3: Grout Type 2 LWF (10/3/13) Weights

Ingredient	Batched Weight (lb)
Water	20.223
Cement	26.990
Coarse Aggregate	0
Water Content: %	0
Fine Aggregate	44.4
Water Content: %	4.58

Table A-4: Grout Type 2 LWF (10/3/13) Volumetric Analysis

Ingredient	Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water	14.815	1.00	0.237
Cement	26.990	3.15	0.137
Coarse Aggregate (SSD)	0	-	-
Absorption: %	0	-	-
Fine Aggregate (SSD)	49.808	1.89	0.422
Absorption: %	17.31	-	-
Total	91.613	-	0.796

Table A-5: Grout Type 3 LWF (10/7/13) Weights

Ingredient	Batched Weight (lb)
Water	24.478
Cement	34.999
Coarse Aggregate	0
Water Content: %	0
Fine Aggregate	44.4
Water Content: %	4.22

Table A-6: Grout Type 3 LWF (10/7/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		18.712	1.00	0.300
Cement		34.999	3.15	0.178
Coarse Aggregate (SSD)		0	-	-
Absorption:	%	0	-	-
Fine Aggregate (SSD)		50.166	1.88	0.429
Absorption:	%	17.76	-	-
Total		103.8765	-	0.907

Table A-7: Grout Type 4 NWC (8/22/13) Weights

Ingredient		Batched Weight (lb)
Water		18.783
Cement		29.000
Coarse Aggregate		43.2
Water Content:	%	0.046
Fine Aggregate		71.8
Water Content:	%	1.20

Table A-8: Grout Type 4 NWC (8/22/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		17.856	1.00	0.286
Cement		29.000	3.15	0.148
Coarse Aggregate (SSD)		43.837	2.62	0.268
Absorption:	%	1.52	-	-
Fine Aggregate (SSD)		72.090	2.59	0.446
Absorption:	%	1.61	-	-
Total		162.783	-	1.148

Table A-9: Grout Type 5 LWC (10/12/13) Weights

Ingredient		Batched Weight (lb)
Water		29.957
Cement		32.000
Coarse Aggregate		28.4
Water Content:	%	0.200
Fine Aggregate		50.4
Water Content:	%	3.91

Table A-10: Grout Type 5 LWC (10/12/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		19.184	1.00	0.307
Cement		32.000	3.15	0.163
Coarse Aggregate (SSD)		32.191	1.74	0.296
Absorption:	%	13.6	-	-
Fine Aggregate (SSD)		57.381	1.87	0.493
Absorption:	%	18.3	-	-
Total		140.756	-	1.259

Table A-11: Grout Type 6 LWC (10/14/13) Weights

Ingredient		Batched Weight (lb)
Water		35.965
Cement		41.494
Coarse Aggregate		28.4
Water Content:	%	0.20
Fine Aggregate		50.4
Water Content:	%	3.91

Table A-12: Grout Type 6 LWC (10/14/13) Volumetric Analysis

Ingredient	Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water	25.193	1.00	0.404
Cement	41.494	3.15	0.211
Coarse Aggregate (SSD)	32.191	1.74	0.296
Absorption: %	13.6	-	-
Fine Aggregate (SSD)	57.381	1.87	0.493
Absorption: %	18.3	-	-
Total	156.259	-	1.403

Table A-13: Grout Type A LWF (5/24/13) Weights

Ingredient	Batched Weight (lb)
Water	30.842
Cement	33.600
Coarse Aggregate	0
Water Content: %	0
Fine Aggregate	83.8
Water Content: %	1.06

Table A-14: Grout Type A LWF (5/24/13) Volumetric Analysis

Ingredient	Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water	20.069	1.00	0.322
Cement	33.600	3.15	0.171
Coarse Aggregate (SSD)	0	-	-
Absorption: %	0	-	-
Fine Aggregate (SSD)	94.573	1.80	0.843
Absorption: %	14.0	-	-
Total	148.2415	-	1.336

Table A-15: Grout Type B NWF (7/6/13) Weights

Ingredient		Batched Weight (lb)
Water		13.924
Cement		16.546
Coarse Aggregate		0
Water Content:	%	0
Fine Aggregate		67.4
Water Content:	%	0.72

Table A-16: Grout Type B NWF (7/6/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		13.171	1.00	0.211
Cement		16.546	3.15	0.084
Coarse Aggregate (SSD)		0	-	-
Absorption:	%	0	-	-
Fine Aggregate (SSD)		68.153	2.57	0.425
Absorption:	%	1.8	-	-
Total		97.8700	-	0.720

Table A-17: Grout Type C LWC (7/17/13) Weights

Ingredient		Batched Weight (lb)
Water		30.787
Cement		24.025
Coarse Aggregate		35.8
Water Content:	%	0.15
Fine Aggregate		59.4
Water Content:	%	6.36

Table A-18: Grout Type C LWC (7/17/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		18.376	1.00	0.294
Cement		24.025	3.15	0.122
Coarse Aggregate (SSD)		40.607	1.73	0.377
Absorption:	%	13.6	-	-
Fine Aggregate (SSD)		67.003	1.88	0.571
Absorption:	%	20.0	-	-
Total		150.011	-	1.365

Table A-19: Grout Type D LWC (9/17/13) Weights

Ingredient		Batched Weight (lb)
Water		31.978
Cement		24.500
Coarse Aggregate		36.60
Water Content:	%	0.134
Fine Aggregate		61.4
Water Content:	%	4.18

Table A-20: Grout Type D LWC (9/17/13) Volumetric Analysis

Ingredient		Weight (lb)	Specific Gravity	Volume (ft^3)
Free Water		19.177	1.00	0.307
Cement		24.500	3.15	0.125
Coarse Aggregate (SSD)		41.566	1.74	0.383
Absorption:	%	13.72	-	-
Fine Aggregate (SSD)		69.234	1.88	0.591
Absorption:	%	17.48	-	-
Total		154.478	-	1.406

APPENDIX B. COMPRESSIVE STRENGTH SPECIMENS PICTURES

The following figures show the results of all cylinder compression strength tests and supplement Table 10 and Table 15. The fracture pattern of each break was observed and recorded.

(a) Specimen 1 **(b) Specimen 2** **(c) Specimen 3** **(d) Specimen 4**

Figure B-1: Grout Type 1 NWF (6/11/13) @ 28-day Failure

(a) Specimen 1 **(b) Specimen 2** **(c) Specimen 3** **(d) Specimen 4**

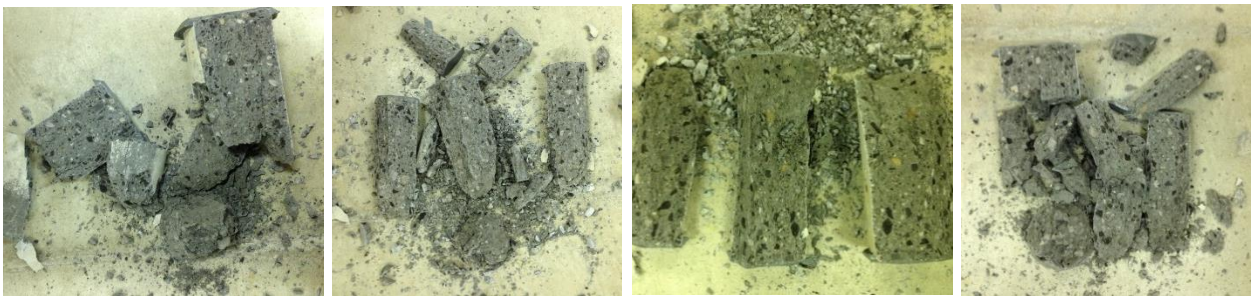
Figure B-2: Grout Type 2 LWF (10/3/13) @ 28-day Failure

(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

Figure B-3: Grout Type 3 LWF (10/7/13) @ 28-day Failure

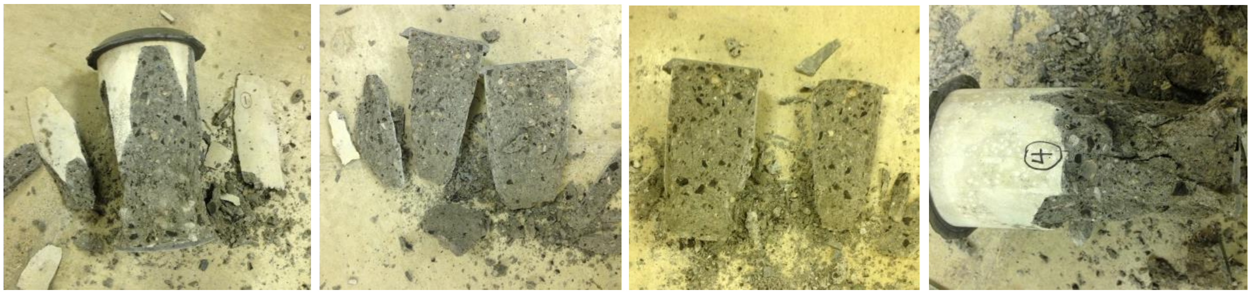
(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

Figure B-4: Grout Type 4 NWC (8/22/13) @ 28-day Failure



(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

Figure B-5: Grout Type 5 LWC (10/12/13) @ 28-day Failure



(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

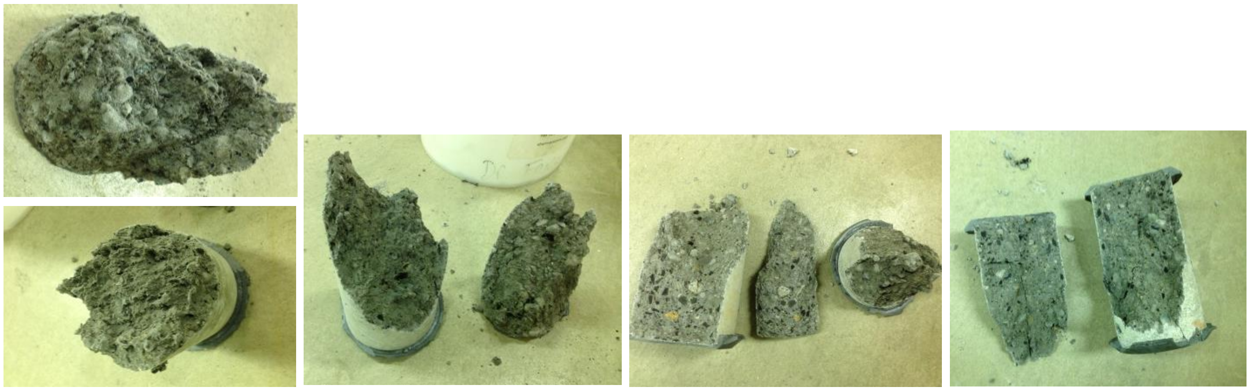
Figure B-6: Grout Type 6 LWC (10/14/13) @ 28-day Failure

(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

Figure B-7: Grout Type A LWF (5/24/13) @ 28-day Failure

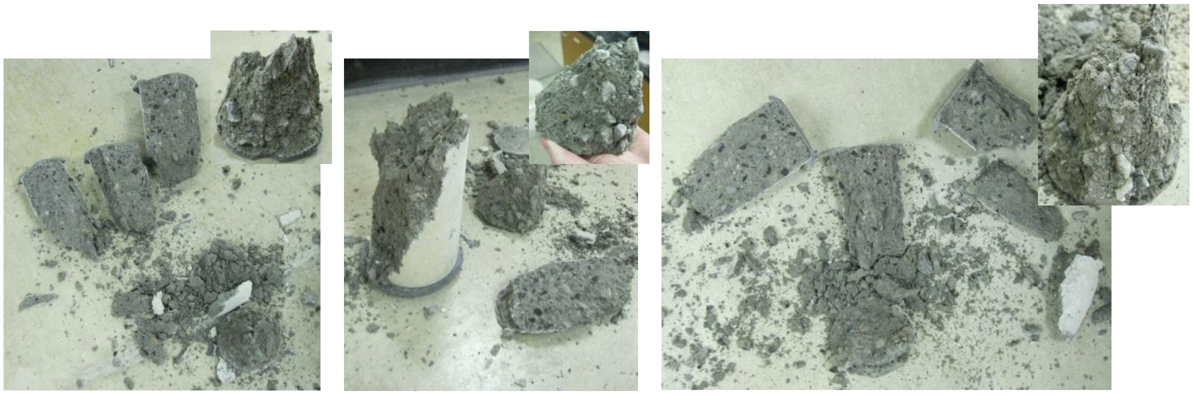
(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4

Figure B-8: Grout Type B NWF (7/6/13) @ 28-day Failure



(a) Specimen 1 **(b) Specimen 2** **(c) Specimen 3** **(d) Specimen 4**

Figure B-9: Grout Type C LWC (7/17/13) @ 28-day Failure



(a) Specimen **(b) Specimen 2** **(c) Specimen 3**

Figure B-10: Grout Type D LWC (9/17/13) @ 28-day Failure (Specimen 4 not pictured)