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A Pilot Study to Determine the Performance of Tension Lap Splices in Reinforced Masonry Made with Light-Weight Grout

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A Pilot Study to Determine the Performance of
Tension Lap Splices in Reinforced Masonry

Made with Light-Weight Grout

Brandon Richard Corbett

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

A Pilot Study to Determine the Performance of Tension Lap Splices in Reinforced Masonry Made with Light-Weight Grout

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Master of Science

The use of light-weight building materials in modern construction has resulted in efficient designs and considerable cost savings by reducing structural weight and supporting sections. This has only been possible because of many years of research to better understand the properties of the light-weight material, and its structural behaviors. However, light-weight grout is a relatively new building material in reinforced masonry construction and little is known about its structural properties. The main objective of this study was to determine if the use of light-weight grout would impact the performance of reinforcing steel, specifically development length, in masonry construction.

The research included testing masonry wallettes made with normal and light-weight grout containing No. 4 (12 mm) bars with splice lengths as prescribed by the current design equation as well as splices with a modification factor. The modification factor was based on preliminary grout testing, using the procedure given in the concrete building code. The wallettes were tested in a tension test to determine if the splices were of sufficient length to fully develop the yield stress of the reinforcement.

For small bar sizes, No. 4 or smaller, it is not necessary to include a modification factor when calculating development length. The minimum length of lap of 12 in. governs when No. 4 or smaller bars are used, and provides sufficient length to fully develop the yield stress of the reinforcement both for normal and light-weight grout types.

Keywords: light-weight grout, development length, modification factor

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1 INTRODUCTION

1.1 Modern Masonry Construction

Modern construction has benefited from the improvements of building materials such as steel and reinforced concrete. Many of today's largest building projects would not be possible without these vital materials and the years of research (Bjorhovde 2004). However, not all projects require these types of materials and often a simpler, more economical material can be used. One such material is masonry; one of the oldest building materials, which still finds wide use today. Its simplicity of construction, versatility, aesthetics, and natural fire protection are a few of its characteristics, which make it an ideal building material (Lourenço et al. 1998).

The basic components of masonry construction are masonry units, mortar, grout, and reinforcing steel. The strength and performance of the masonry structure are dependent on the interaction of these components (Masonry Standards Joint Committee 2013). Masonry units may be made from a variety of materials, the most common being stone, concrete, clay, and glass. Typical masonry units have holes or cells in them, which allow for the placement of reinforcing steel and grout. The addition of the steel and grout provides masonry structures with additional axial and shear capacity. The purpose of the mortar is to bond the individual units together.

Grout is a fluid cementitious mixture which bonds adjacent masonry units and bonds the steel reinforcement to the masonry. Grout is required to have a slump of 8 to 11 inches (200 to 280 mm) to ensure a flowable mixture (ASTM Standard C476 – 10). The bond between the grout

and reinforcing steel is vital to the overall strength of the masonry system (Mitchell and Marzouk 2007). Under maximum loading it is advantageous to have the reinforcement yield first so that a catastrophic failure of the masonry is avoided. In order to ensure that the reinforcement yields, it is necessary that it be anchored in such a way that it does not slip free from the grout. The chemical and physical bonds between the grout and reinforcement must be strong enough to resist these forces. This is achieved by embedding the reinforcement a specified distance, called development length, into the grout such that the contact between the grout and reinforcement will be over an area large enough to develop the bond strength to anchor the reinforcement, thus allowing the steel to yield. Development length of reinforcing steel embedded in grout is calculated according to requirements given in the *Building Code Requirements and Specification for Masonry Structures* (ACI/ASCE/TMS 2013). When it is necessary to overlap consecutive portions of steel reinforcement, the length of overlap or splice, as required by the building code, is also the development length. The terms splice, lap-splice, and development length will be used synonymously in this thesis.

1.2 Research Motivation

Light-weight concrete is commonly used in buildings, bridges, and offshore platforms. Light-weight material has also been used in the manufacturing of concrete masonry units (CMU) but light-weight material is not widely used for grout. Generally, light-weight material is more expensive than the normal-weight alternatives, but the overall reduction in structural weight can mean additional savings by reducing supporting sections and foundations, and less reinforcement (Holman 2001). These benefits of using light-weight material could be applied to masonry walls by using light-weight grout.

While much research has been performed on normal-weight concrete and grout, there are no standards for light-weight grout and previous research on its behavior is very limited. The current design equation for development length was derived from tests on normal-weight grout. Reinforced concrete research; however, has moved on to include the effects of light-weight concrete on development length, which has resulted in a modification factor being added to the development length equation for reinforcing steel embedded in concrete. The premise for adding the modification factor is that light-weight concretes have lower splitting strengths, and so development lengths will need to be larger (McCormac and Brown 2014). Research such as this has yet to be conducted using light-weight grout, and no modification factor, if any is needed, currently exists in the masonry building code to correct for the possible effects light-weight grout may have on development length.

Since there is little research on light-weight grout, a pilot experimental program was designed to increase the knowledge base of its characteristics. The main objective of this study was to determine if the use of light-weight grout would impact the performance of the reinforcing steel. The research included testing masonry wallettes made with normal and light-weight grout containing reinforcement with splice lengths as prescribed by the current design equation as well as splices with a new modification factor. The wallettes containing normal-weight grout were used as the control group. The loads at failure were used to calculate the stresses within the reinforcement to determine if they had yielded, and comparisons were made with the control group.

1.3 Scope of Research

This pilot project is limited to the testing of light-weight 8-inch concrete masonry units reinforced with lap spliced No. 4 (12-mm) Grade 60 reinforcing bars and filled with light-weight grout. The reinforcing splice was centered within the masonry cell and positioned at the mid-height of the test panels. Testing was completed by subjecting each specimen to a monotonic load in direct tension, at a displacement controlled rate. Loading was continued until failure occurred.

To reduce possible variations in the grout mix design, a preliminary testing program was implemented to determine the properties of the normal and light-weight grouts. This was achieved by using packaged concrete bags, and both a normal and light-weight concrete bag mix with similar compressive strengths were available for this research. Normal and light-weight grouts were made using 80-lb. bags of the 5000 Plus High Strength Concrete Mix and Maximizer Concrete, respectively. Grout was made by adding water to each of these mixes until the slump was within the target of 8 to 11 inches (200 to 280 mm).

Once the grout properties were established, a total of nine wallettes were designed and built, each with tension lap splices spaced 16 inches on center. The reinforcement used in all wallettes were No. 4 (12-mm) bars. There were two groups of wallettes, each group consisting of nominally identical wallettes. The first group was the Control Group, containing normal-weight grout and existing code-length splices. The second group, Test Group 1, was built with light-weight grout but with splice lengths calculated using the modification factor. The wallettes were built and allowed to cure for 28 days. After 28 days the wallettes were tested in a tension test to determine if the splices were of sufficient length to fully develop the yield stress of the reinforcement.

1.4 Outline of Thesis

This thesis is organized into six chapters. Previous research and background information are discussed in Chapter 2. Chapter 3 describes the materials selection, specimen construction, and testing methods and procedures. The chapter also describes the preliminary tests which were conducted to determine the properties of the grout. The results of all testing are presented in Chapter 4. Chapter 5 discusses the results compiled from the study, and summarizes the general failure modes and performance of the test specimens. Conclusions and recommendations for future research are presented in Chapter 6.

2 BACKGROUND

2.1 General Literature Review

The following sections present a brief review of the literature pertaining to the design and behavior of lap splices in reinforced masonry. The current design equation for development length is relatively young with significant changes in recent years. The materials reviewed include the work of several organizations, building codes, research reports and textbooks.

2.1.1 Masonry Limit States Design Standard

In the early 1990's, the Masonry Standards Joint Committee (MSJC) began work to develop a new limit states design standard for masonry. The relationship for splice length used by the Masonry Limit States Design Standard (MLSDS) was originally developed by Soric and Tulin (1987), who modeled the hollow concrete masonry units as thick-walled pressure vessels and the radial stress due to bond action on the grout as the hydraulic pressure. In its original form, the required lap length is as follows:

$$l_d = \frac{C d_b^2 f_y}{(t-d_b) f_{gt}} \quad (1)$$

where:

t	=	masonry thickness;
f_{gt}	=	grout tensile strength;
d_b	=	reinforcing bar diameter;
f_y	=	steel yield strength; and
C	=	empirical constant.

The empirical constant C accounts for nonuniformity of bond stresses along the length of the bar. Soric and Tulin (1987) conducted tests with No. 4 and No. 7 bars in 6-in. concrete masonry units and calculated a mean value of 1.75 for the constant C. The MLSDS adopted this value for C and assumed a grout tensile strength of 400 psi (2.75 MPa). With these values, the equation becomes:

$$l_d = \frac{0.0045 d_b^2 f_{ye}}{(t-d_b)} \geq 12 \text{ inches} \quad (2)$$

where: f_{ye} = expected yield strength of the steel.

The proposed formula, adopted in the draft MLSDS, considered the important parameters of grout tensile strength, reinforcement yield strength, and the thickness of the grouted masonry.

2.1.2 Construction Productivity Advancement Research

A cooperative effort between the U.S. Army Corps of Engineers and Atkinson-Noland and Associates (Hammons et al. 1994) conducted research to validate the proposed equation. The research was conducted under the auspices of the Construction Productivity Advancement Research (CPAR) program and covered multiple areas of masonry design; the first of which was that of lap-splice requirements for reinforced masonry.

The tests conducted by CPAR were focused on investigating parameters which could possibly affect the strength and ductility of lap splices. These parameters included masonry unit width, masonry unit type, reinforcing bar diameter, and lap length. A total of 124 specimens were tested for 62 different combinations of these parameters. Specimens were constructed in stack bond using half units to produce a single vertical cell. The range of lap lengths and specimen sizes for both concrete and clay masonry units are shown in Figure 1.

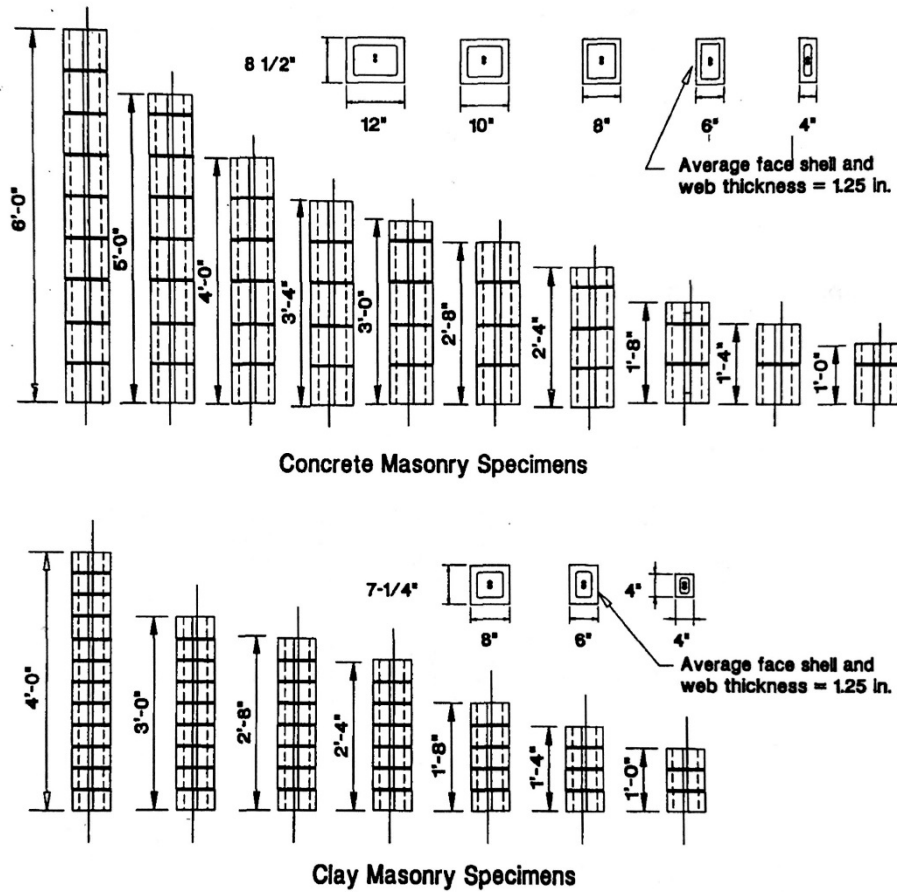


Figure 1. CPAR Lap Lengths and Specimen Sizes

The test setup for the lap-splice study was intended to subject the reinforcing bars to pure tension. Tensile loads were applied directly to the bars in a displacement controlled rate. A schematic of the overall test setup is shown in Figure 2.

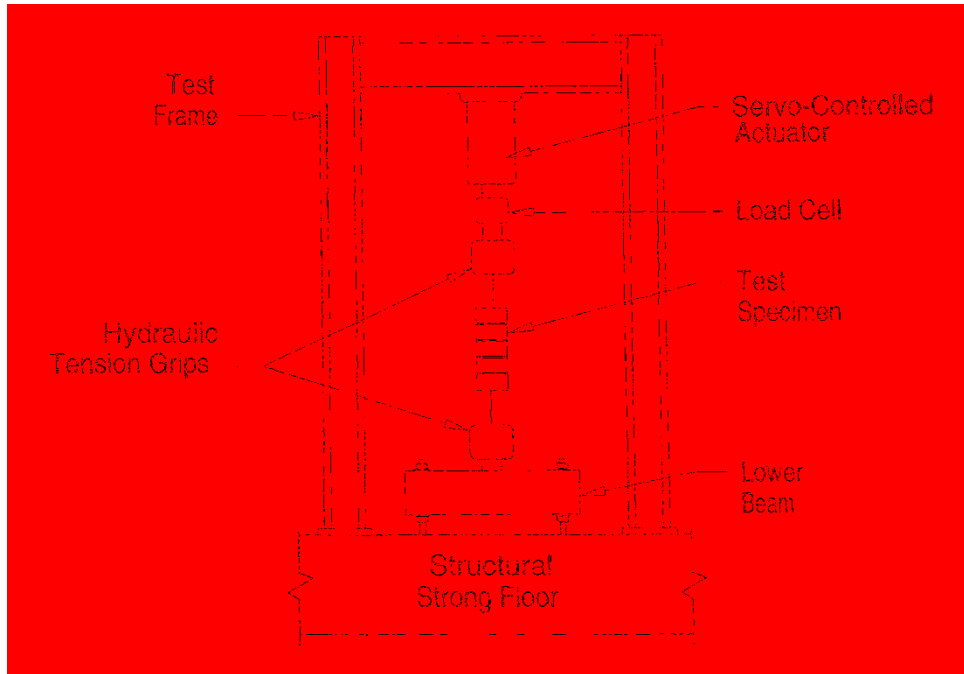


Figure 2. CPAR Tension Test Setup

Two main conclusions were made upon completion of the CPAR project. First, increasing the unit width, and therefore the minimum cover, increased the load capacity of the splice; it also meant that increasing the diameter of the reinforcement, thereby reducing the minimum cover, increased the potential for splitting of the masonry assemblage. Second, the proposed equation, Equation 2, in general, under-predicted the required length of lap for spliced reinforcement.

2.1.3 National Concrete Masonry Association

In 1994, the Uniform Building Code (UBC) updated its provisions for minimum splice length. The new equation for development length was the following strength design expression:

$$l_{de} = \frac{0.15 d_b^2 f_y}{K \sqrt{f'_m}} \leq 52 d_b \quad (3)$$

and:

$$l_d = \frac{l_{de}}{\phi} \geq 12 \text{ inches} \quad (4)$$

where:

l_d	=	development length of reinforcement, in.;
ϕ	=	strength reduction factor; equal to 0.80;
l_{de}	=	basic development length, in.;
d_b	=	diameter of reinforcing bar, in.;
f_y	=	tensile yield stress of reinforcement, psi;
K	=	reinforcement clear cover or clear spacing, whichever is less, and not greater than $3d_b$, in.; and
f'_m	=	specified compressive strength of masonry at age of 28 days, psi.

The limit of $52 d_b$ in Equation 3, is a permitted maximum that allows lap splice lengths to be shorter than would be required by the formula directly.

Also in 1994, the National Concrete Masonry Association (NCMA) began a testing program to re-evaluate the UBC code equation (Thomas et al. 1999). The purpose of the research was to investigate the effects of different combinations of masonry material strength, splice length, cover depth, and diameter of reinforcement. Masonry panels were constructed using 8-inch and 12-inch CMU with reinforcing bars of sizes ranging from No. 4 through No. 9. Test groups were constructed with three specimens per set, with varying combinations of cover depth and lap splice length. The masonry panels were constructed in running bond. To ensure equally distributed tensile loads, the test frame was built with a “T” joint for the hydraulic pumps. Loads were then applied at a constant rate until failure occurred. A schematic of the test setup is shown in Figure 3.

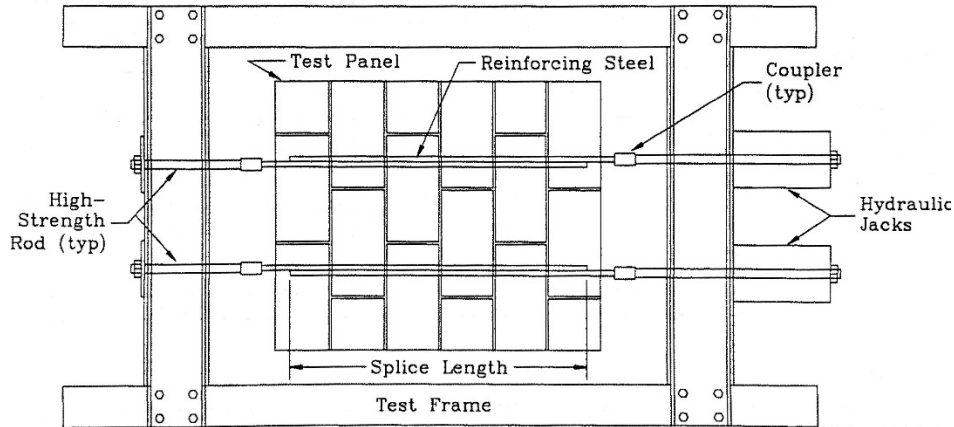


Figure 3. NCMA Tension Test Setup

General conclusions reported were that cover, bar diameter, compressive strength of the masonry, and grade of reinforcement significantly affect the performance of lap splice.

Researchers also concluded that the UBC equation for calculating the required length of lap overestimated the lap length for smaller diameter bars and underestimated the lap length for larger bars.

2.1.4 Washington State University

A testing program was being conducted at Washington State University concurrently with that being conducted at NCMA (Thompson 1997). The purposes of the research were to verify and complement that being conducted at NCMA, as well as develop, if needed, new equations for splice length based on the results of several independent research programs.

Testing was limited to 8-inch normal-weight CMU reinforced with No. 5 and No. 7 grade 60 bars. Various lap lengths were tested, with reinforcing splices located in the center of the

masonry cell. Nine different specimen sets were constructed, each with three identical replicates. A sample of the panel dimensions is shown in Figure 4.

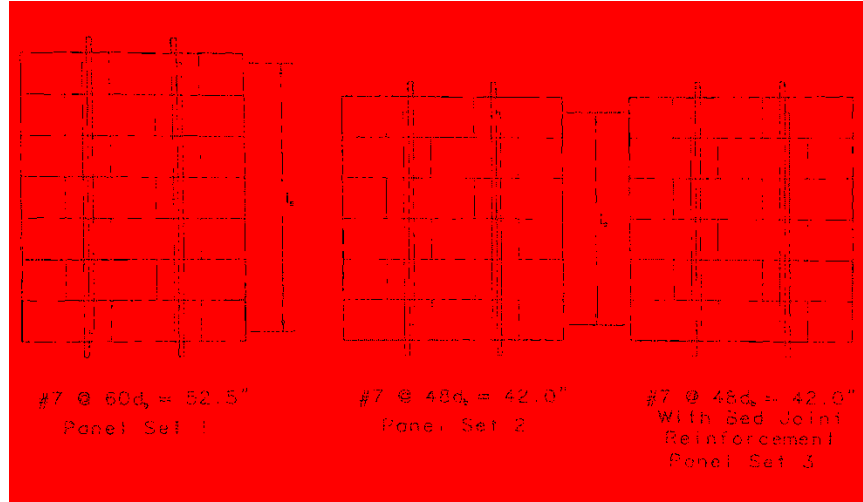


Figure 4. WSU Lap Lengths and Panel Dimensions

Testing was completed by subjecting each specimen to a monotonic load in direct tension in a manner very similar to that used in the NCMA testing program. A schematic of the test setup is shown in Figure 5. The results of the tests conducted at WSU were then combined with those conducted at NCMA and those during the CPAR project. Together, the compiled database consisted of more than 150 individual specimens. Several linear and multiple linear regressions were conducted in an attempt to represent the behavior of lap splices. Based on the results of the analyses, a new development length design equation, which more accurately represented the performance of tension lap splices in reinforced concrete masonry, was developed.

$$\phi l_s = \frac{0.15 d_b f_y \gamma}{K \sqrt{f'_m}} \geq 12 \text{ inches} \quad (5)$$

where:

γ	=	1.0 for No. 3 through No. 6 reinforcing bars;
γ	=	1.4 for No. 7 through No. 11 reinforcing bars;
ϕ	=	strength reduction factor; equal to 0.80;

- K = $c_{cl}/d_b \leq 5.0$;
 c_{cl} = minimum clear cover, in.;
 d_b = diameter of reinforcement, in.
 f'_m = ultimate compressive strength of masonry assemblage, psi; and
 l_s = length of lap splice.

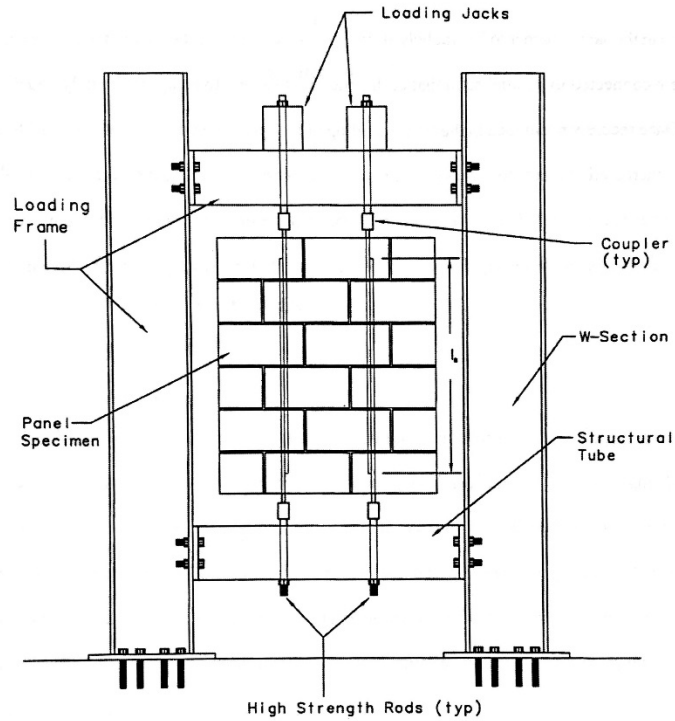


Figure 5. WSU Tension Test Setup

Equation 5 introduced a new variable, γ , to the design of lap splices. The weakness of the UBC equation was that it unsuccessfully predicted lap lengths for all bar sizes; the addition of the γ factor corrected the weakness by increasing the splice length for larger diameter bars.

2.1.5 Masonry Standards Joint Committee

In the current *Building Code Requirements and Specification for Masonry Structures* (ACI/ASCE/TMS 2013) the following equation is used for development length of uncoated bars:

$$l_d = \frac{0.13 d_b^2 f_y \gamma}{K \sqrt{f'_m}} \geq 12 \text{ inches} \quad (6)$$

where:

γ	=	1.0 for No. 3 (M#10) through No. 5 (M#16) reinforcing bars;
γ	=	1.3 for No. 6 (M#19) through No. 7 (M#22) reinforcing bars;
γ	=	1.5 for No. 8 (M#25) through No. 9 (M#29) reinforcing bars;
K	=	shall not exceed the smallest of: minimum masonry cover, clear spacing between adjacent reinforcement splices, and $9 d_b$;
d_b	=	diameter of reinforcement, in.;
f'_m	=	ultimate compressive strength of masonry assemblage, psi; and
l_d	=	development length.

Code Section 9.3.3.4 states that the minimum length of lap for bars shall be 12 in.

(305mm) or the development length determined by Equation 6, whichever is greater. When used correctly, lap splices are to develop a minimum of 125% of the specified yield strength of the bar. Currently, there are no modification factors or commentary for addressing the use of light-weight grout and its impact on development length in the current building code.

2.2 Standard Specifications for Grout and Mortar

The standard specification for grout is given in ASTM C476 (Standard Specification for Grout for Masonry) and ASTM C404 (Standard Specification for Aggregates for Masonry Grout). There are two types of grout, fine and coarse. Fine aggregates are all those which pass the 9.5-mm (3/8-in) sieve and coarse aggregates all must pass the 12.5-mm (1/2-in.) sieve. Fine grout is made with all fine aggregates, and coarse grout is made with fine and coarse aggregates. Grout may be specified by proportion or strength. When specified by strength, a minimum compressive strength of 2,000 psi (13.79 MPa) is required. Determination of grout compressive strength is explained in ASTM C1019 (Standard Test Method for Sampling and Testing Grout) and ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). According to ASTM C476, grout must also have a slump of 8 to 11 inches (200 to

280 mm). Slump is measured according to the method described in ASTM C143 (Standard Test Method for Slump of Hydraulic-Cement Concrete).

The standard specification for mortar is explained in ASTM C270 (Standard Specification for Mortar for Unit Masonry). Mortar may be specified either by proportion or by property. Within the proportion and property specification, ASTM C270 further classifies masonry mortar by Type. Designations are M, S, N, and O. Type S and N are most commonly used for modern construction (Masonry Standards Joint Committee 2013). According to ASTM C270, Type S mortar cement must have a minimum average compressive strength at 28 days of 1800 psi (12.4 MPa) and a flow of $110 \pm 5\%$. Determination of mortar compressive strength and flow are explained in ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)), and ASTM C1437 (Standard Test Method for Flow of Hydraulic Cement Mortar), respectively.

2.3 Tensile Strength of Light-Weight Concrete

Section 8.6 of the *Building Code Requirements for Structural Concrete* (ACI Committee 318 2011) provides guidelines on the use of light-weight concrete and corresponding light-weight concrete modification factor λ . Research has shown that light-weight concretes have lower tensile strengths, which can reduce shear strength, friction properties, splitting resistance, and bond strength between concrete and reinforcement (Hanson 1961). The modification factor λ reflects the lower tensile strength of light-weight concrete. If light-weight concrete is used in the design of a reinforced concrete structure, this factor is 0.75, resulting in the development length being 33% longer than that for normal-weight concrete.

The concrete code provides a procedure for determining λ , based on the relationship between the average splitting tensile strength, f_{ct} , and the specified compressive strength, f'_c , for the light-weight concrete being used. The equation for determining λ is:

$$\lambda = \frac{f_{ct}}{6.7 \sqrt{f'_c}} \quad (7)$$

The splitting tensile strength of concrete is determined through split-cylinder tension tests per ASTM C496 (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens). The formula for calculating the splitting tensile strength is:

$$T = \frac{2P}{\pi ld} \quad (8)$$

where:

T	=	splitting tensile strength (f_{ct}), psi;
P	=	maximum applied load, lbf;
l	=	length, in; and
d	=	diameter, in.

2.4 Summary

The development length equation for reinforced masonry has evolved over time. In an effort to contribute to the research previously conducted, this pilot project used the procedure as given in Section 8.6 of the *Building Code Requirements for Structural Concrete* to calculate a modification factor λ for light-weight grout, and conducted tests to determine if it would impact the performance of the reinforcement.

3 TEST PROCEDURE

The following sections include information describing the selection, testing, and use of materials in the manufacturing of mortar, grout, wallettes, and prisms.

3.1 Materials Selection

Material selection was based on ASTM standards. To minimize possible variations in mix design, materials for grout and mortar were made from ready-mix bags. Both a normal and light-weight concrete bag mix with similar compressive strengths were used in this pilot research program. Normal and light-weight grouts were made using 80 lb. bags of the 5000 Plus High Strength Concrete Mix and Maximizer Concrete, respectively. These ready mix bags were chosen based on their relatively close compressive strengths. The compressive strengths were 5000 psi and 5500 psi respectively for the normal and light-weight grouts. Grout was made by adding water to each of these mixes until the slump was within the target of 8 to 11 inches (200 to 280 mm). Type S mortar was also made from a ready-mix bag from Sakrete. Pictures of these bags can be seen in Figure 6.



Normal Weight Grout



Light Weight Grout



Type S Mortar

Figure 6. Grout and Mortar Selection

The reinforcing steel and CMU were donated by BAR-US Rebar Splice Solutions and Oldcastle, respectively. The selection of the No. 4 (12 mm) bar for the tests was motivated primarily by the size of the wallettes and testing apparatus. Larger bar sizes would have resulted in longer splice lengths and larger wallettes, requiring additional equipment, which were not available. The steel reinforcement supplied by BAR-US Splice Solutions was made with upset threads. These threads allowed for simple connections between the wallette and testing apparatus without any loss of cross-sectional area of the bar. Upset threads are made by cutting the rebar end square, then enlarging the end by cold forging. The end is then cut threaded by a bench threading machine. A picture of the reinforcement with the upset threads is shown in Figure 7.



Figure 7. Typical Upset Threads

3.2 Preliminary Grout Testing

To determine the grout properties, preliminary testing was conducted on both normal and light-weight grout types. The same mixing procedures were followed for each batch. For each test, a single 80-lb. bag was emptied into a concrete mixer and mixing water was added incrementally until a slump of 8 to 11 inches (200 to 280mm) was achieved. Total mixing time was monitored so that over-mixing was avoided. Typical mixing time was between 4 and 5 minutes. The remaining water was then weighed so as to determine the total amount of water added to the mix. Samples from the mix were then taken to measure the grout properties.

The slump, air content, and unit weight were measured following ASTM C143, ASTM C231 (Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method), and ASTM C138 (Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete), respectively, and cylindrical specimens were prepared according to ASTM C192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). The cylinders were allowed to cure for a 24 hour period, after which the molds were removed and the concrete cylinders were placed in a fog room until testing. Testing was conducted after 7 days. On the day of testing, all cylinders were capped following ASTM C617, and tested in accordance with ASTM C39. Typical fracture patterns were noted for each grout test, as shown in Figure 8. The results are summarized in Table 2. Complete results from all tests specimens are shown in Table A - 5.

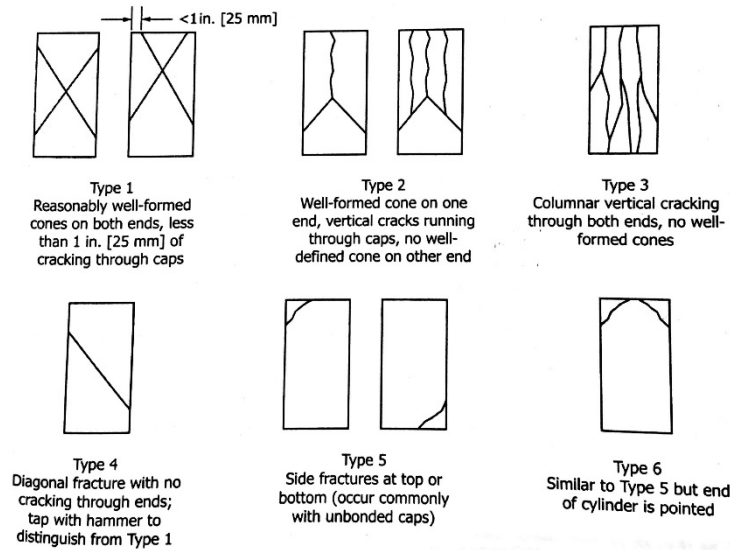


Figure 8. Typical Fracture Patterns

The first objective of these preliminary tests was to define the compressive strength of each type of grout, and make modifications if necessary so that approximately equal compressive strengths were achieved between the normal and light-weight grout. After the first round of tests, it was determined that the normal weight grout had a lower average compressive strength, as was expected based on the bag mix. To increase its compressive strength additional tests were done in which portions of Type I/II cement were added to the ready-mix bags prior to mixing. The tests were iterated until a suitable design was determined corresponding to a specific amount of cement being added which resulted in a compressive strength which was comparable to that of the light-weight grout. A total of 4 preliminary tests were performed, one for the light-weight grout, and three for the normal weight.

The second objective of the preliminary grout tests was to establish a modification factor (λ) for the light-weight grout based on its compressive and splitting tensile strength. Split-cylinder testing was done according to ASTM C496. The test setup is shown in Figure 9.

Calculation of the splitting tensile strength as well as the modification factor were done following Equations 7 and 8, respectively.



Figure 9. Split-Cylinder Test

3.3 Reinforcement Testing

Before it was possible to calculate splice lengths, it was necessary to verify the yield strength and ultimate tensile strength of the reinforcement. Three separate samples from the reinforcement were tested according to ASTM E8 (Standard Test Method for Tension Testing of Metallic Materials). Two of the samples were tested past their yield strength but not to ultimate load, and one specimen was tested until failure. Stress-Strain curves were developed for each of these tests and the yield strength of the reinforcement was determined by using a 0.2% offset method. According to ASTM A615 (Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement) grade 60 bars are to have a minimum yield strength of 60 ksi, and a minimum ultimate tensile strength of 90 ksi.

3.4 Specimen Construction

The wallettes were built over a period of several days. During the first day a professional mason constructed the 10 wallettes using 8-in. CMU with Type S mortar in running bond pattern. For ease of construction each panel was built atop a 2-in. by 12-in. wooden base supported by three 8-in. half-blocks. The wooden bases were fabricated with dimension lines for the correct placement of the CMU and pre-drilled holes for the reinforcement to pass through. The construction can be seen in Figure 10. Masonry prisms were also constructed during the first day by the mason in accordance with ASTM C1314 (Standard Test Method for Compressive Strength of Masonry Prisms) and are shown in Figure 11.

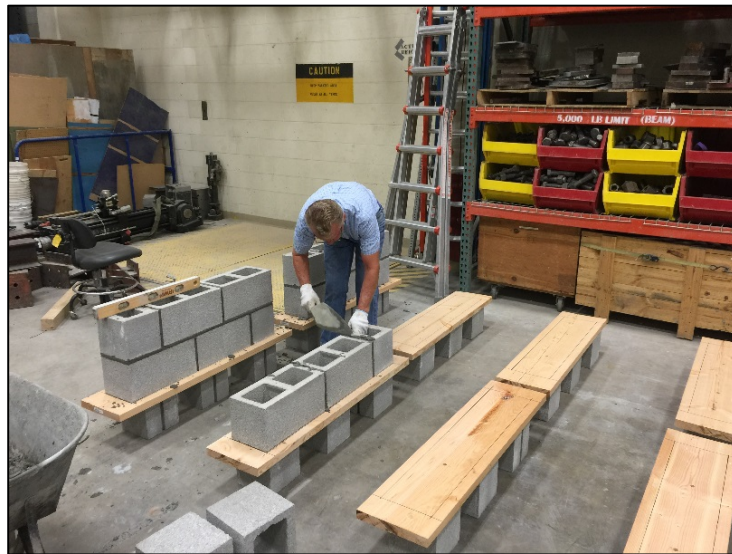


Figure 10. Construction of Wallettes



Figure 11. Masonry Prisms Prior to Grouting

Once the wallettes were completed they were checked for level, and the mortar joints finished with a concave tool. Figure 12 shows the wallettes prior to grouting. The wallettes were left to cure for two days before grouting commenced.



Figure 12. Wallettes Prior to Grouting

During the time the wallettes were curing, the reinforcement splices were fabricated. Total reinforcement lengths were designed so that each specimen was the same total height. This was done so that the testing frame would not need to be altered for each test. The design of each wallette was based on calculated splice lengths. The first group was the Control Group, containing normal-weight grout and existing code-length splices. The second group, Test Group 1, was built with light-weight grout but with splice lengths calculated using the modification factor. Drawings of the specimens are shown in Figure 13. Each group consisted of nominally identical wallettes.

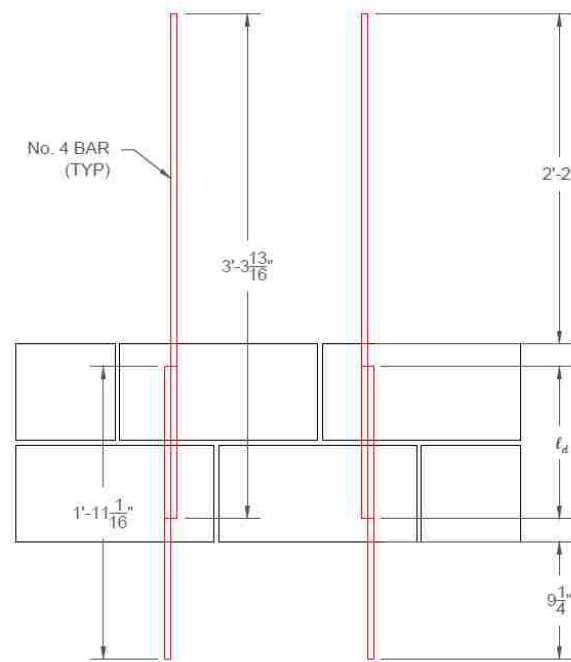


Figure 13. Wallette Design

The values used for calculating the development length are shown in Table 1. The total lengths of each reinforcing bar, as shown in Figure 13, were then fabricated. Each bar was cut to

its specified length and labeled. Splices were made by attaching corresponding bars with bailing wire. A picture of a typical splice is shown in Figure 14.

Table 1. Development Length Calculations

Grout Type	d_b in.	f_y ksi	γ	K	f_m Assumed psi	λ	$l_{d,calc}$ in.	$l_{d,min}$ in.	$l_{d,used}$ in.
NW	0.472	60	1	3.577	2500	1.0	9.72	12.0	12.0
LW	0.472	60	1	3.577	2500	0.85	11.66	12.0	12.0



Figure 14. Typical Reinforcement Splice

Grouting took place after two days of curing. Grouting was done over a two-day period. Grout was made following the same procedures during preliminary grout testing. Each batch was made by combining multiple ready-mix bags and sufficient water until the slump was satisfactory. The amount of water added to each batch was based on the preliminary tests, and exact amounts were recorded along with the slump for each batch. Samples from the batches were used for making grout prisms, and for filling the masonry prisms. Batch numbers were created so that placement of the grout into specific numbered wallettes could be noted. Pictures of the mixing process and grout composition are shown in Figure 15.



Figure 15. Grout Mixing and Composition

Placement of the grout into the wallettes was accomplished by filling buckets with grout from the batch and pouring them into the cells of the masonry. Reinforcement had been previously placed within the cells, with portions protruding from the top and bottom of the wallettes for testing. The reinforcement rested on the floor, and was supported by the wooden base for vertical alignment, as shown in Figure 16.



Figure 16. Placement of Reinforcement Prior to Grouting

The masonry cells were cleaned from mortar droppings prior to grouting. The filling of masonry cells with grout is shown in Figure 17. After the masonry cells were filled, a vibrator was used to consolidate the grout. A single vertical pass was used for each cell; this is shown in Figure 19. After consolidation, additional grout was placed in the cells to level-off the surfaces. Consolidation of this top layer was done by using a metal tamping rod, as shown in Figure 18.

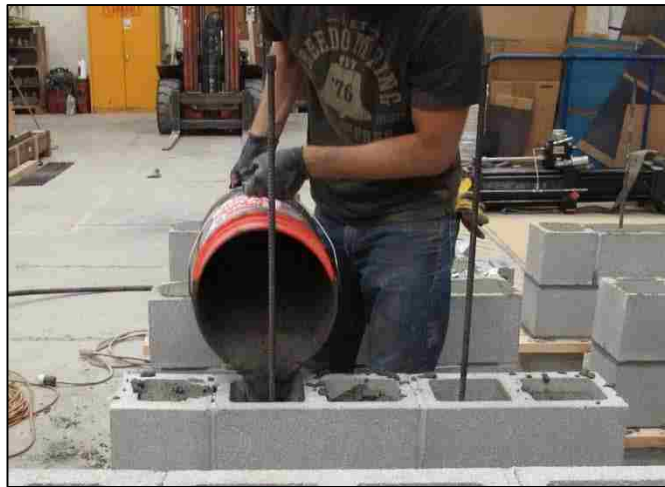


Figure 17. Pouring Grout into Walette



Figure 18. Filling Top Portion of Walette



Figure 19. Consolidation of Grout using Vibratory Stinger

Masonry prisms were filled during the first and second days of grouting, as well as the construction of grout prisms. Grout prisms were made in accordance with ASTM C1019. The completed grout and masonry prisms are shown in Figure 20. Three samples from each of the normal and light-weight grout batches were used to make a total of 6 grout prisms. Two masonry prisms were built for each type as well: normal weight, light-weight and hollow.



Figure 20. Grout and Masonry Prisms

Grouting was completed after two days and the specimens were allowed to cure for 28 days prior to testing. All wallettes were labeled with grout type and wallette number for identification. Due to the number of reinforcing bars, only 9 wallettes were completed; the Control Group contained 4 specimens while Test Group 1 contained 5 specimens. The completed wallettes are shown in Figure 21.



Figure 21. Completed Wallettes Prior to Testing

3.5 Specimen Testing

The following sections describe the standard procedures which were followed to determine material properties and strengths. Since there are no standards for testing masonry wallettes in tension, this section also describes the testing methods and procedures which were used to determine the stresses within the reinforcement.

3.5.1 Mortar Testing

The composition of the mortar was closely monitored by the mason, and samples were taken from each batch for testing. Mortar flow was first tested in accordance with ASTM C1437. Flow table specifications were in accordance with ASTM C230 (Standard Specification for Flow Table for Use in Tests of Hydraulic Cement). This test is shown in Figure 11. Once adequate flow was achieved, mortar cubes were cast, cured and tested following ASTM C109. Mortar cubes were tested in a Forney compression testing machine.



Figure 22. Mortar Flow Tests

3.5.2 Grout and Masonry Prism Testing

Grout slump was measured for each batch according to ASTM C143. Grout prisms were made according to ASTM C1019 and tested in accordance with ASTM C39. Testing was completed 28 days after construction of the grout specimens. Prior to testing, all grout and masonry prisms were measured, and then capped with gypsum cement according to ASTM

C1552 (Standard Practice for Capping Concrete Masonry Units, Related Units, and Masonry Prisms for Compression Testing). Figure 23 shows the grout and masonry prisms with gypsum caps prior to testing.



Figure 23. Capping of Grout and Masonry Prisms

The testing apparatus which was used to determine compressive strengths for the grout and masonry prisms was a Baldwin Universal Testing Machine (UTM). All prisms were centered in the testing device and a steel plate was placed on the top bearing surface between the specimen and the spherical bearing block. This setup is shown in Figure 24 for a typical masonry prism. Failure modes were noted for each masonry prism according to those shown in Figure 25.



Figure 24. Test Setup for Grout and Masonry Prisms

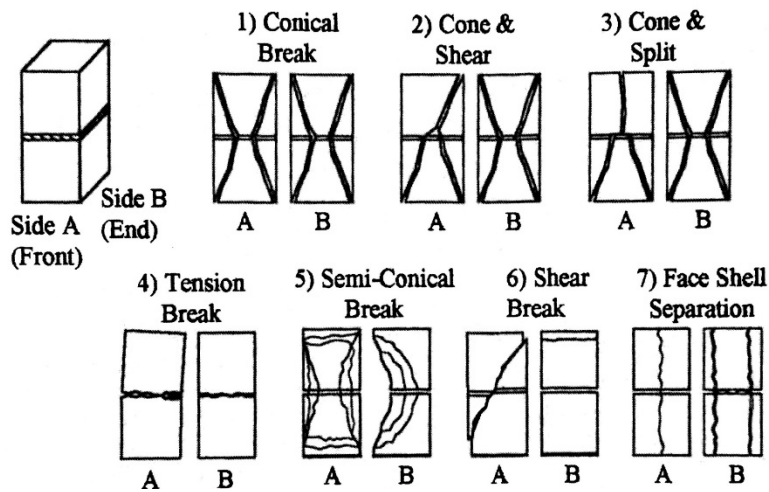


Figure 25. Masonry Prism Failure Modes

3.5.3 Wallette Testing

Common methods of testing splices include pull-pull and flexural testing. A typical flexural test configuration includes third-point transverse loading of a test specimen such that the

splice is in a region of approximately constant moment. This type of test can influence the modes of failure, such as crushing the compression face prior to failure of the splice. For this reason, a pull-pull testing scenario was used. A Baldwin UTM was used to apply the tensile loads. This testing configuration is similar to that used in the research conducted by others (Hammons et al. 1994) and (Thomas et al. 1999). Although this monotonic tensile loading may represent an extreme loading condition for the splice reinforcement, it allows for observation of the mode of failure and performance of the splice.

Loading was applied at a displacement controlled rate until failure occurred and the load significantly decreased. Figure 26 shows the testing configuration. A loading rate of 0.02 in. /min. was applied until the load exceeded 24 kips. The loading rate was then increased to 0.16 in. /min. until failure. The average total time required to load a specimen to failure was approximately thirty minutes. General failure modes were also noted for each specimen. Load and displacement data were attained from the computer connected to the UTM.

Connecting each wallette specimen to the loading frame was accomplished in the following steps. The specimen was transported by a forklift with the aid of industrial lifting straps. The specimen was centered between the tension crosshead and the adjustable crosshead, and then raised to the top channel member, and secured with steel washers and couplers as shown in Figure 26. The forklift was then lowered several inches so that the specimen was suspended vertically by the top connections. The forklift and straps were left in this position for the duration of the test so that when failure occurred the specimen would be prevented from falling. The adjustable crosshead on the UTM was then raised vertically to align the bottom connections, which were also secured with steel washers and couplers. The connections are

shown in detail in Figure 27. Images of the steel channels, plates and washers are shown in Figure 28. These images show the connections as detailed in Figure 26.

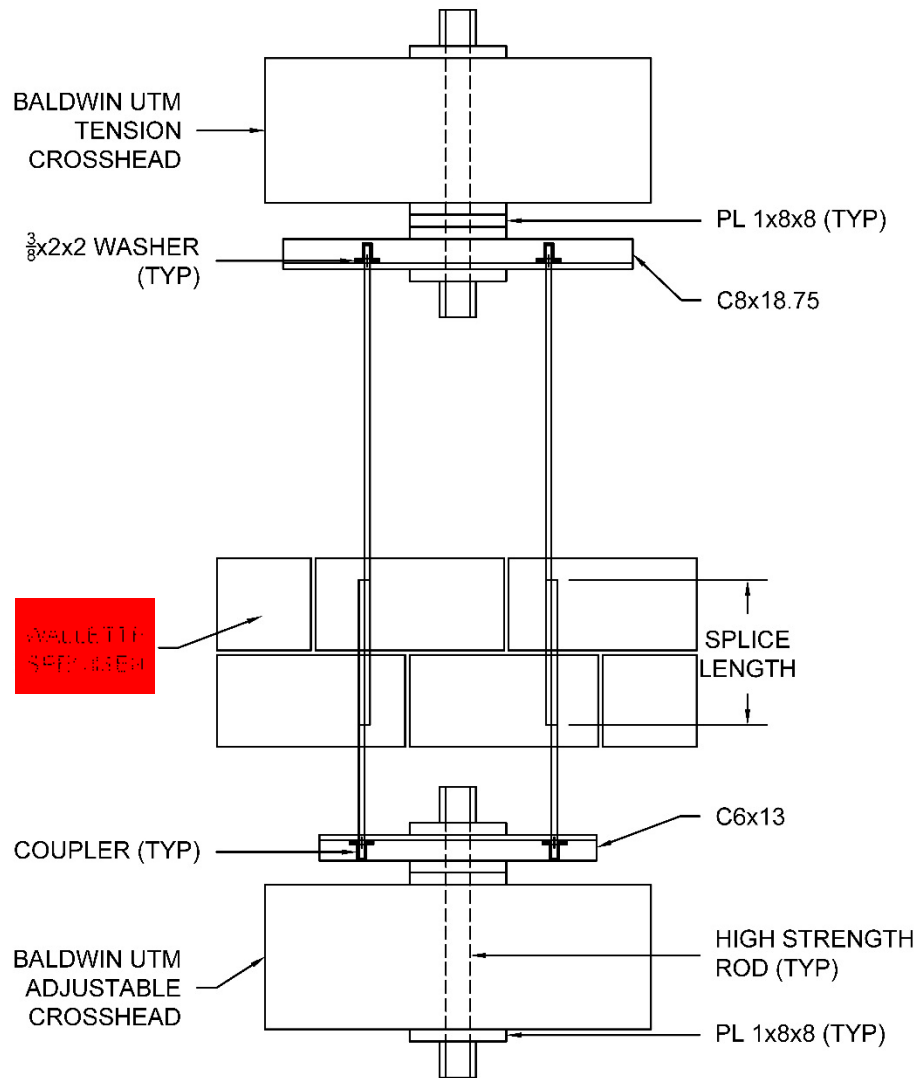


Figure 26. Wallette Testing Setup



Figure 27. Connection of the Wallette Specimen to the Test Frame

The steel channels were fabricated with slots on either side, as shown in Figure 28, to accommodate the small variance in the distance between reinforcement. The center hole in the channel allowed for the high strength rod to pass through. Steel plates were used as spacers between the UTM and the channels so that the couplers could be reached and also to increase the overall stiffness of the connection.



Figure 28. Channels, Washers, Steel Plates and High Strength Rods

4 RESULTS

The following sections present the results from all testing procedures as previously described. Additional tables, figures, and photos can be found in Appendices A and B.

4.1 Preliminary Grout Testing

Results from the preliminary grout testing for compressive strength are presented in Table 2. Also shown in Table 2 are the mix designs for each batch type, including the amounts of water and cement which were added, and the resulting slump. Detailed results for each batch can be found in Appendix A.

Table 2. Preliminary Compressive Strength Testing Results

Grout Type	Date		Water Added (lb.)	Cement Added (lb.)	Slump (in.)	Average Compressive Strength, f _c (psi)
	Prepared	Tested				
LW - 1	6/16/2015	6/23/2015	24.2	-	10.25	3190
NW - 1	6/17/2015	6/24/2015	10.6	0.0	9.50	2340
NW - 2	6/25/2015	7/2/2015	11.8	3.0	9.00	4630
NW - 3	7/9/2015	7/16/2015	10.1	1.4	9.50	2920

Presented in Table 3 are the results from the split-cylinder tests. The modification factor, λ , was calculated using Equation 7, with the results from batch 1 of light-weight grout. The exact value calculated was 0.89. As a conservative measure, this value was changed to 0.85. With

$\lambda = 0.85$, the splice length would be 20% longer for wallettes containing light-weight grout.

Results from all split-cylinder tests can be found in Appendix A, Table A - 6.

Table 3. Split-Cylinder Testing Results

Grout Type	Date Prepared	Date Tested	Water Added (lb.)	Cement Added (lb.)	Slump (in.)	Average Splitting Tensile Strength, f_{ct} (psi)
LW - 1	6/16/2015	6/23/2015	24.2	-	10.25	335

4.2 Reinforcement Testing

Results from the steel tension tests showed that the minimum yield strength of the reinforcement was 60 ksi and the ultimate tensile strength was 95 ksi. A sample Stress-Strain curve is shown in Figure 29. Additional Stress-Strain curves for all reinforcement tests are located in Appendix A. The results satisfy the requirements of ASTM A615.

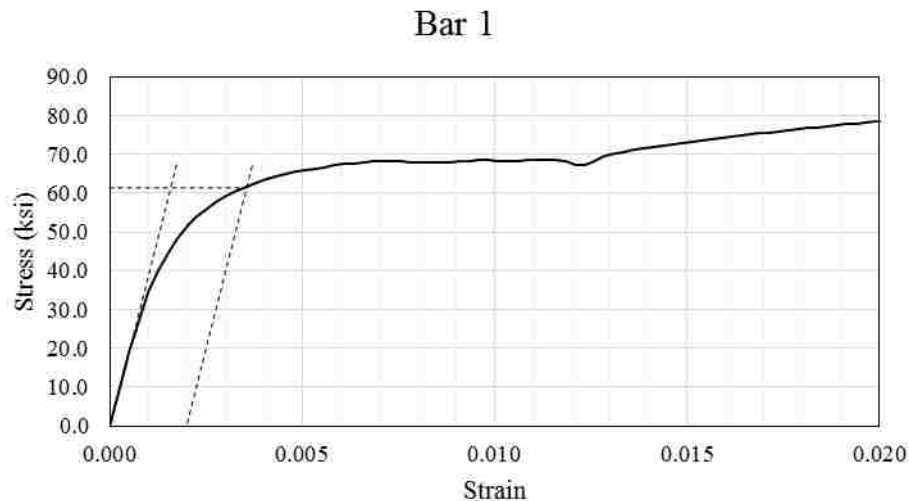


Figure 29. Sample Stress-Strain Curve

4.3 Specimen Testing

The following subsections present the results from the specimen testing procedures for mortar, grout and masonry prisms, and the wallettes. Pictures from these tests can be seen in Appendix B.

4.3.1 Mortar Testing

Presented in Table 4 are the results from the mortar flow and compression testing. The complete table showing individual mortar compressive tests is found in Appendix A. A typical mortar cube specimen after testing is shown in Appendix B.

Table 4. Mortar Flow and Compressive Strength

Batch ID	Flow (%)	Compressive Strength (psi)
A	108	2120
B	105	2160
C	106	2150

4.3.2 Grout and Masonry Prism Testing

Presented in Table 5 are the grout mix designs and classifications for each type. This table shows the resulting slump, walette number and masonry or grout prism which was constructed from the specific batch.

Table 5. Grout Mix Design and Classification

Batch ID	Mortar Batch	Grout Type	# Bags	Water Added (lb.)	Cement Added (lb.)	Slump (in.)	Wicket Filled	Grout Prism	Masonry Prism
1	A	NW	3	30.8	4.2	9.50	2	NW 1	NW 1
2	A	NW	3	29.0	4.2	8.50	1	NW 2	
3	A	NW	3	29.6	4.2	9.25	3	NW 3	
4	B	NW	3	31.0	4.2	9.50	4		NW 2
5	B	LW	4	89.8	-	10.00	5 & 6	LW 1	
6	C	LW	4	84.6	-	9.50	7 & 8	LW 2	LW 1
7	C	LW	2	41.2	-	9.75	9	LW 3	LW 2

The compressive strength results for the grout prisms are presented in Table 6. This table presents the dimensions of all specimens as well as the failure mode, associated with Figure 8.

Table 6. Grout Prism Compression Test Results

Grout Prism ID	Average Width (in.)	Average Length (in.)	Area (in ²)	Maximum Load (lb)	Failure Mode	Compressive Strength (psi)
NW 1	4.25	4.25	18.06	68156	Type 1	3770
NW 2	4.13	4.25	17.53	104588	Type 4	5970
NW 3	4.00	3.94	15.75	64304	Type 1	4080
Average Compressive Strength						4610
LW 1	4.13	4.13	17.02	86799	Type 3	5100
LW 2	4.00	4.00	16.00	94077	Type 3	5880
LW 3	4.19	4.13	17.27	130898	Type 3	7580
Average Compressive Strength						6190

The data from the UTM was also used to generate a graph showing load vs. displacement for the grout prisms, as shown in Figure 30. Black and red lines denote normal and light-weight grout types, respectively.

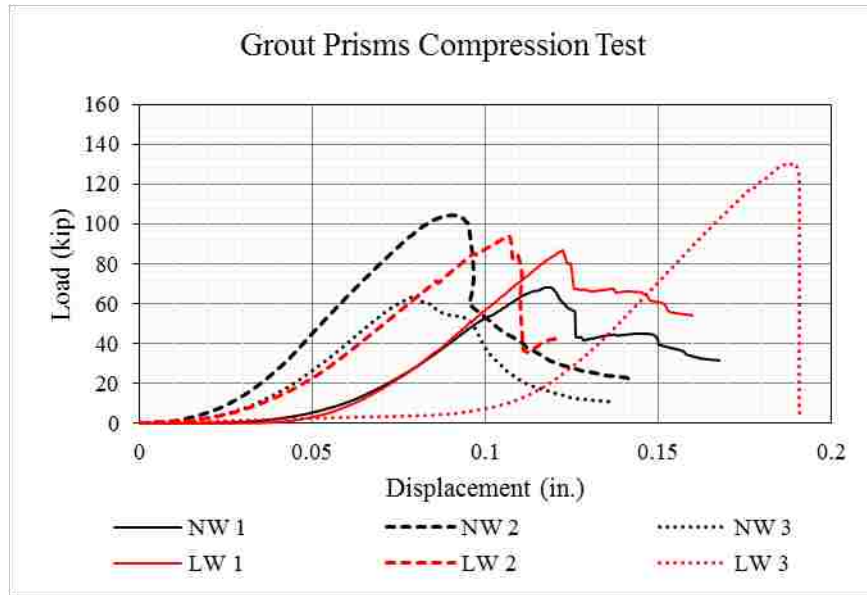


Figure 30. Load vs. Displacement for Grout Prisms

The results from the masonry prism compression testing are presented in Table 7. This table presents the dimensions of each masonry prism, maximum load at failure, failure mode as detailed in Figure 25, as well as the average compressive strength for each masonry prism. The data from the UTM was used to generate a graph showing load vs. displacement for the masonry prisms, and is shown in Figure 31; prisms H1 and H2 were hollow masonry prisms. With the true values of masonry compressive strength, calculations of development length were repeated, and are shown in Table 8.

Table 7. Masonry Prism Compression Test Results

Masonry Prism ID	Average Height (in.)	Average Width (in.)	Average Length	Area (in ²)	Maximum Load (lb)	Failure Mode	Compressive Strength (psi)
NW 1	16.00	7.63	7.63	58.14	147947	Mode 7	2540
NW 2	16.00	7.63	7.63	58.14	171664	Mode 7	2950
Average Compressive Strength							2750
LW 1	16.00	7.63	7.63	58.14	208896	Mode 7	3590
LW 2	16.00	7.63	7.63	58.14	201950	Mode 7	3470
Average Compressive Strength							3530
Hollow 1	16.00	7.63	7.63	29.31	95821	Mode 7	3270
Hollow 2	16.00	7.63	7.63	29.31	96134	Mode 7	3280
Average Compressive Strength							3280

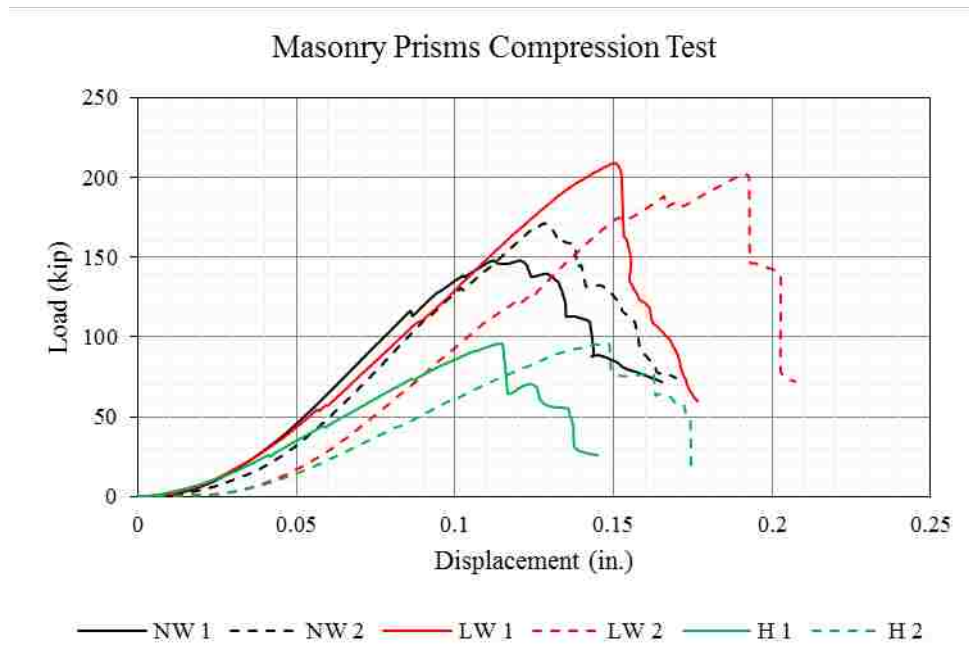


Figure 31. Load vs. Displacement Plot for Masonry Prisms

Table 8. Development Length Calculations with Masonry Compressive Strengths

Grout Type	d_b in.	f_y ksi	γ	K	f'_m Calc psi	λ	$l_{d,calc}$ in.	$l_{d,min}$ in.	$l_{d,used}$ in.
NW	0.472	60	1	3.577	2750	1.0	9.27	12.0	12.0
LW	0.472	60	1	3.577	3530	0.85	9.81	12.0	12.0

4.3.3 Wallette Testing

For each wallette specimen, applied loads were recorded by the computer software controlling the UTM, and the corresponding reinforcement stresses were calculated. General failure modes were noted, and the stress values were related to the measured yield strength of the reinforcing bars as a reference. Table 9 summarizes this information for the wallette testing. General failure modes which were observed included reinforcement fracture, longitudinal splitting of the masonry, and failure of the threaded ends of the reinforcement.

Table 9. Wallette Failure Summary

Test Group	Wallette ID	Splice Length	General Failure Mode	Maximum Load (lb.)	Load per Bar (lb.)	Failure Stress (ksi)	% of Yield at Failure
Control	1	12.00	Bar Fracture	32626	16313	93.2	155
	2		Bar Fracture/Long. Split	31841	15921	91.0	152
	3		Bar Fracture	31966	15983	91.3	152
	4		Bar Fracture	32437	16218	92.7	154
Average				32217	16109	92.1	153
Group 1	5	12.00	Longitudinal Split	29102	14551	83.2	139
	6		Bar Fracture/Long. Split	31927	15963	91.2	152
	7		Bar Thread Failure	29388	14694	84.0	140
	8		Bar Fracture/Long. Split	32038	16019	91.6	153
	9		Bar Thread Failure	29604	14802	84.6	141
Average				30739	15206	86.9	145

Using the data from the UTM, load vs. displacement plots were generated for each group of wallette specimens. These plots are presented in Figure 32 and Figure 33 for the Control Group and Test Group 1, respectively. Photographs showing the failure modes have been cataloged in Appendix B.

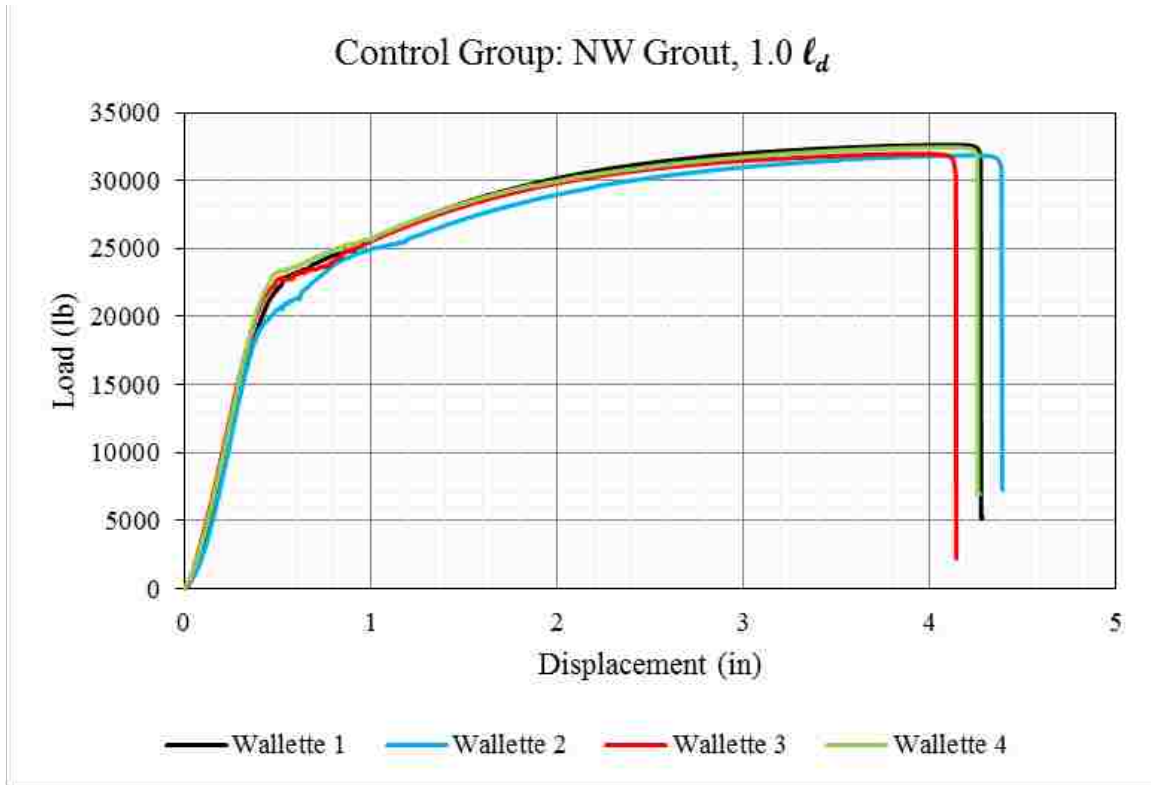


Figure 32. Load vs. Displacement Plot for Control Group

Group 1: LW Grout, $1.2 \ell_d$

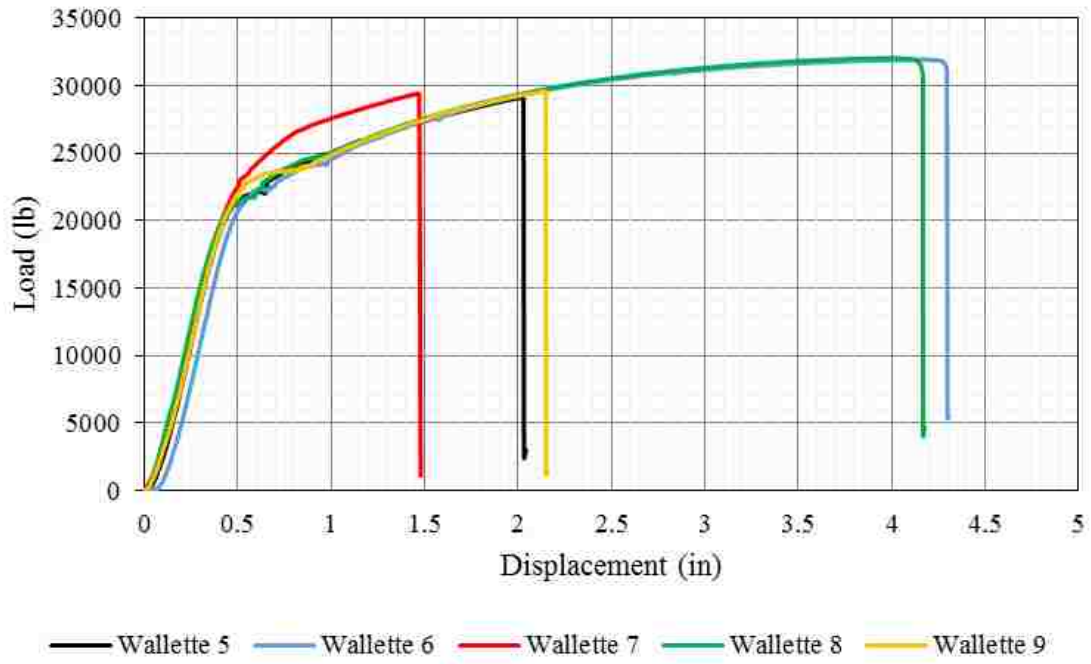


Figure 33. Load vs. Displacement Plot for Group 1

5 DISCUSSION

The results presented in Chapter 4 are discussed and analyzed in this chapter. Results from the grout and mortar testing are compared to applicable ASTM standards, and comparisons between the normal and light-weight grout are made. Based on these comparisons, the results from the wallette tension tests are also analyzed with their failure modes to determine possible correlations.

5.1 Mortar and Grout General Standards

The mortar used in this research study was Type S, mortar cement. After determining mortar flow and compressive strength, it is concluded that the mortar used meets applicable ASTM standards both for flow and compressive strength. The average flow of all samples taken was 106 %, with an average compressive strength of 2140 psi, both of which meet the requirements as prescribed in ASTM C270.

The type of grout used in this study was coarse grout, and meets the requirements of ASTM C476, and ASTM C404. As shown in section 4.3.2, all grout batches meet the requirements of slump and 28-day compressive strength as explained in ASTM C476 and ASTM 1019.

5.2 Grout Compressive Strength

One of the main objectives of the preliminary grout testing program was to establish a suitable mix design for the normal and light-weight grout types which would result in equivalent compressive strengths. With comparable compressive strengths, it would then be possible to determine a modification factor to establish the difference between their individual splitting-tensile strengths. The results from the preliminary grout tests satisfied this main objective as shown in Table 2. The average 7-day compressive strengths for the NW-3 and LW-1 batches were 2920 and 3190 psi, respectively. These compressive strengths were felt to be suitably equivalent and these mix designs were used for the walletes.

Grout prism testing showed that the average 28-day compressive strengths of the normal and light-weight grouts were 4610 psi and 6190 psi respectively. The difference between these values was considerably greater than it had been after the preliminary grout tests. This may have been caused by the differences in the types of molds which were used to cast the specimens; in the preliminary grout tests, plastic cylindrical molds were used, but the 28-day grout prisms were cast with CMU molds. The plastic molds would not have allowed for any water to be lost through absorption as would have been the case for the grout prisms. This may have affected the water-cement (w/c) ratio and the grouts' curing process. Compressive strength is directly related to the w/c ratio, and the ability of the cement to completely hydrate during the curing process (Mindess et al. 2003). Generally, concrete mix designs with lower w/c ratios result in greater compressive strengths, but the use of CMU molds would cause the mix to lose some water to the mold through absorption. The normal weight grout mix may not have been able to completely hydrate all of the cement which was added; resulting in a lower compressive strength. The amount of water absorbed by the CMU molds should be the same regardless of grout type,

however; the light-weight grout required more than double the amount of water as compared to the normal weight mix, so the percentage of water lost to the mold would not have produced such a noticeable affect as it would for the normal weight grout.

Since the compressive strengths of the normal and light-weight grout were not equivalent, the calculated modification factor was not an accurate representation between the normal and light-weight grout splitting tensile strength.

5.3 Masonry Compressive Strength

The compressive strength of the masonry ($f'm$) is one of the variables in Equation 6, which is used to calculate the development length. The compressive strength is influenced by the strength of the mortar, CMU, and grout. As was discussed in the previous section, it was determined that the normal and light-weight grouts had very different compressive strengths, so it would be expected that the resulting compressive strengths of the masonry would also be different for their respective types. From Table 7, it can be seen that the average compressive strengths of the masonry containing normal and light-weight grouts were 2750 psi, and 3530 psi, respectively. Comparing the differences between the grout and masonry compressive strengths, the ratio of the masonry strengths is less than the ratio of grout strengths, $3530/2750 = 1.28$ and $6190/4610 = 1.34$, because of the influence of the mortar and CMU.

Generally, larger values of masonry compressive strength result in shorter development lengths. However, due to other variables, such as bar size, these values of $f'm$ result in the same development lengths being calculated by Equation 6 due to the minimum length of lap of 12 in. These calculations are shown in Table 8.

5.4 Wallette Testing

While every attempt was made to construct symmetric, uniform wallette specimens, variations in material properties created slightly non-uniform specimens. It was expected then that there would be some discrepancies in performance between individual wallettes. The results from each group, however, corresponded well with each other, and the overall performance from the tests are felt to be acceptable.

The results from the Control Group were very similar. As shown in Figure 32, the load paths of all specimens were nearly identical, with a linear slope in the elastic region, and then tapering off until ultimate failure of the reinforcement. Each of these specimens experienced the same failure mode, fracture of the reinforcement. Only Wallette 2 showed longitudinal splitting, but this may have been the consequence of the bar rupturing, and the release of the specimen from the test frame. Prior to failure, Wallette 2 showed no sign of cracking, so it is believed that this splitting of the masonry was the result of the release of the wallette from the test frame. Within the Control Group the average failure stress was 153% that of the yield strength of the reinforcement.

The results from Test Group 1 were not as similar as those from the Control Group, although there were some general patterns. Wallettes 6 and 8 behaved nearly identical as those from the Control Group; linear slope in the elastic region, and then tapering off until ultimate failure of the reinforcement, but Wallettes 5, 7, and 9 had different failure modes. These three wallettes failed at approximately 30 kips as seen in Figure 33. Wallettes 7 and 9 had similar failure modes of bar thread failure. At their maximum loading, the threads were stripped from the reinforcement by the couplers. The reason for this failure mode is unknown, but it may be that the coupler was not completely threaded with the reinforcement, preventing the bar from

developing its ultimate capacity. The last wallette from this group, Wallette 5, experienced a longitudinal split failure. While the failure modes varied amongst this group, the average failure stress was 145% that of the yield strength of the reinforcement.

6 CONCLUSIONS

6.1 Summary

A pilot testing program was conducted to determine the performance of lap splices in reinforced masonry made with light-weight grout. The project included material testing to determine the properties of the grout and to determine a modification factor that would account for the use of light-weight grout in masonry construction. Testing was completed by subjecting each specimen to a monotonic load in direct tension, at a displacement controlled rate. A total of nine wallettes were designed, built, and tested, to determine if the splices were of sufficient length to develop a minimum of 125% of the yield strength of the reinforcement.

6.2 Findings

While this study was not an extensive testing program, based on the material properties used in this study, which were grout type and its compressive strength, and reinforcing bar size, the following general conclusions can be made:

1. The splices which were placed in light-weight grout were of sufficient length to develop more than 125% of the yield strength, but it is not possible to determine if the modification factor was instrumental in this; the development length was governed by the minimum length of lap of 12 in.

2. For small bar sizes, No. 4 or smaller, it is not necessary to include a modification factor in the formula for development length since the minimum length of lap will allow the bar to fully develop the yield stress.
3. Current code provisions adequately calculate the required length of lap for spliced reinforcement in normal weight grouted masonry. All specimens in the Control Group were able to develop an average failure stress of 153% of the yield stress of the reinforcement, surpassing the minimum value of 125%.

6.3 Recommendations for Future Research

Additional testing of specimens would need to be done to more fully address the performance of lap splices in reinforced masonry with light-weight grout. It is recommended that future testing be done in a similar manner to that used in this project so that results can be compared. The following topics are suggested for future research:

1. Only one bar size was used in this study, but multiple bar sizes would need to be tested to determine the effects light-weight grout may have on reinforcement of all sizes. Due to the size of bar used in this project, the development length was governed by the minimum length of 12 in.; larger bars should be used so that the resulting development length is greater than the minimum length of lap.
2. During preliminary testing of grout, cylinders and prisms should be cast. Grout prisms will lose some water to the CMU and will result in more accurate grout compressive strengths.
3. Once the grout properties have been established by preliminary testing, masonry prisms should also be made and tested to establish f'_m prior to building wallets.

4. The compressive strength of the light-weight grout used in this project was much greater than is typically used in masonry construction. It is possible that masonry made with light-weight grouts with lower compressive strengths may result in different results than those of this research. Therefore, light-weight grouts of varying compressive strengths should also be tested.

REFERENCES

- ACI Committee 318. (2011). *Building Code Requirements for Structural Concrete and Commentary* (ACI 318-11). American Concrete Institute, Farmington Hills, MI.
- ACI/ASCE/TMS. (2013). *Building Code Requirements and Specification for Masonry Structures*. American Concrete Institute, Farmington Hills, MI.
- ASTM Standard A615/A615M – 15a, “Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement,” ASTM International, West Conshohocken, PA, 2015.
- ASTM Standard C39/C39M – 14a, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” ASTM International, West Conshohocken, PA, 2014.
- ASTM Standard C109/C109M – 13e, “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens,” ASTM International, West Conshohocken, PA, 2014.
- ASTM Standard C138/C138M – 14, “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete,” ASTM International, West Conshohocken, PA, 2014.
- ASTM Standard C143/C143M – 14, “Standard Test Method for Slump of Hydraulic-Cement Concrete,” ASTM International, West Conshohocken, PA, 2014.
- ASTM Standard C192/C192M – 14, “Standard Specification for Flow Table for Use in Tests of Hydraulic Cement,” ASTM International, West Conshohocken, PA, 2014.
- ASTM Standard C230/C230M – 14, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory,” ASTM International, West Conshohocken, PA, 2014.

ASTM Standard C231/C231M – 14, “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,” ASTM International, West Conshohocken, PA, 2014.

ASTM Standard C270 – 14a, “Standard Specification for Mortar for Unit Masonry,” ASTM International,” West Conshohocken, PA, 2014.

ASTM Standard C404 – 11, “Standard Specification for Aggregates for Masonry Grout,” West Conshohocken, PA, 2014.

ASTM Standard C476 – 10, “Standard Specification for Grout for Masonry,” West Conshohocken, PA, 2014.

ASTM Standard C617/C617M – 12, “Standard Practice for Capping Cylindrical Concrete Specimens,” West Conshohocken, PA, 2014.

ASTM Standard C1019 – 14, “Standard Test Method for Sampling and Testing Grout,” West Conshohocken, PA, 2014.

ASTM Standard C1314 – 14, “Standard Test Method for Compressive Strength of Masonry Prisms,” West Conshohocken, PA, 2014.

ASTM Standard C1437 – 13, “Standard Test Method for Flow of Hydraulic Cement Mortar,” West Conshohocken, PA, 2014.

ASTM Standard C1552 – 14a, “Standard Practice for Capping Concrete Masonry Units, Related Units and Masonry Prisms for Compression Testing,” West Conshohocken, PA, 2014.

Bjorhovde, R. (2004). "Development and use of high performance steel." *Journal of Constructional Steel Research*, 60(3), 393-400.

Hammons, M. I., Atkinson, R. H., Schuller, M. P., and Tikalsky, P. J. (1994). "Masonry Research for Limit-States Design." *Rep. No. CPAR-SL-94-1*, US Army Corps of Engineers.

- Hanson, J. A. (1961). "Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete." *ACI Journal Proceedings*, 58(1), 1-39.
- Holman, J. P. (2001). *Experimental methods for engineers*. McGraw-Hill, Boston.
- Lourenço, P. B., Rots, J. G., and Blaauwendraad, J. (1998). "Continuum Model for Masonry: Parameter Estimation and Validation." *Journal of Structural Engineering*, 124(6), 642-652.
- Masonry Standards Joint Committee. (2013). *Masonry Designers' Guide*. The Masonry Society, Boulder, CO.
- McCormac, J. C., and Brown, R. H. (2014). *Design of Reinforced Concrete*. John Wiley & Sons, Inc., Hoboken, NJ.
- Mindess, S., Young, J., Darwin, D. (2003). *Concrete, 2nd Ed. Pearson College Division*, New Jersey.
- Mitchell, D. W., and Marzouk, H. (2007). "Bond Characteristics of High-Strength Lightweight Concrete." *ACI Structural Journal*, 104(1), 22-29.
- Soric, Z., and Tuilin, L. G. (1987). "Bond and splices in reinforced masonry." TCCMAR Report No. 6.2-2, U.S.-Japan Coordinated Program for Masonry Building Research.
- Thomas, R. D., Gunasekara, H. S., Samblanet, P. J., Thompson, J. J., Breeding, D. L., and Ross, D. H. (1999). "Evaluation of Minimum Reinforcing Bar Splice Criteria for Hollow Clay Brick and Hollow Concrete Block Masonry." *Rep. No. MR 12*, National Concrete Masonry Association.
- Thompson, J. J. (1997). "Behavior and Design of Tension Lap Splices in Reinforced Concrete Masonry". M.S. thesis. Washington State University.

APPENDIX A. RESULTS

Table A - 1. Light Weight Preliminary Batch 1

LW Maximizer Bag	
Batch Prepared	6/16/2015
Water Bucket Empty (lb)	1.8
Initial Bucket Weight with Water (lb)	37.0
Final Bucket Weight with Remaining Water (lb)	12.8
Water Added to Mix (lb)	24.2
Slump (in.)	10.25
Empty Unit Weight Bucket (lb)	5.6065
Full Unit Weight Bucket (lb)	16.6515
Measured Unit Weight (pcf)	110.45
Measured Air Content (%)	4.5

Table A - 2. Normal Weight Preliminary Batch 1

NW 5000 Plus Bag	
Batch Prepared	6/17/2015
Water Bucket Empty (lb)	1.8
Initial Bucket Weight with Water (lb)	34.2
Final Bucket Weight with Remaining Water (lb)	23.6
Water Added to Mix (lb)	10.6
Slump (in.)	9.5
Empty Unit Weight Bucket (lb)	5.606
Full Unit Weight Bucket (lb)	19.835
Measured Unit Weight (pcf)	142.29
Measured Air Content (%)	2.5

Table A - 3. Normal Weight Preliminary Batch 2

NW 5000 Plus Bag with (3 lb) Cement Added	
Batch Prepared	6/25/2015
Water Bucket Empty (lb)	1.8
Initial Bucket Weight with Water (lb)	21.4
Final Bucket Weight with Remaining Water (lb)	9.6
Water Added to Mix (lb)	11.8
Slump (in.)	9
Empty Unit Weight Bucket (lb)	5.6025
Full Unit Weight Bucket (lb)	19.8005
Measured Unit Weight (pcf)	141.98
Measured Air Content (%)	2.5

Table A - 4. Normal Weight Preliminary Batch 3

NW 5000 Plus Bag with (1.4 lb) Cement Added	
Batch Prepared	7/9/2015
Water Bucket Empty (lb)	1.83
Initial Bucket Weight with Water (lb)	29.4
Final Bucket Weight with Remaining Water (lb)	19.3
Water Added to Mix (lb)	10.1
Slump (in.)	9.5
Empty Unit Weight Bucket (lb)	5.61
Full Unit Weight Bucket (lb)	19.8715
Measured Unit Weight (pcf)	142.615
Measured Air Content (%)	3

Table A - 5. Compressive Strength Data from Preliminary Grout Testing

Testing Date	Batch Type	Cylinder No.	Average Diameter (in.)	Average Length (in.)	Area (in ²)	Fracture Type	Compressive Strength (psi)
6/23/2015	LW Batch 1	1	4.03	8.10	12.76	Type 2	3390
		2	4.04	8.15	12.82	Type 2	3680
		3	4.04	8.10	12.82	Type 3	2490
		4	4.04	8.10	12.82	Type 2	3190
		Average Compressive Strength					
6/24/2015	NW Batch 1	1	4.04	7.95	12.82	Type 1	2350
		2	4.03	7.90	12.76	Type 1	2460
		3	4.03	7.95	12.76	Type 1	2150
		4	4.04	8.05	12.82	Type 1	2240
		5	4.04	7.90	12.82	Type 1	2540
		6	4.05	7.85	12.88	Type 1	2270
Average Compressive Strength						2340	
7/2/2015	NW Batch 2	1	4.03	8.05	12.76	Type 2	4640
		2	4.03	8.05	12.76	Type 2	4430
		3	4.03	8.05	12.76	Type 6	4610
		4	4.03	8.10	12.76	Type 1	4670
		5	4.04	8.05	12.82	Type 3	4370
		6	4.03	8.05	12.76	Type 2	5060
Average Compressive Strength						4630	
7/16/2015	NW Batch 3	1	4.03	8.00	12.76	Type 1	2750
		2	4.04	8.00	12.82	Type 2	3090
		3	4.04	7.90	12.82	Type 1	3050
		4	4.03	8.05	12.76	Type 1	2700
		5	4.04	8.05	12.82	Type 1	3020
Average Compressive Strength						2920	

Table A - 6. Splitting Tensile Strength Data from Preliminary Grout Testing

Testing Date	Batch Type	Cylinder No.	Average Diameter (in.)	Average Length (in.)	Area (in ²)	Splitting Tensile Strength (psi)
6/23/2015	LW Batch 1	5	4.02	4.50	12.69	240
		6	4.04	8.10	12.82	360
		7	4.05	8.05	12.88	385
		8	4.04	8.10	12.82	355
Average Splitting Tensile Strength						335

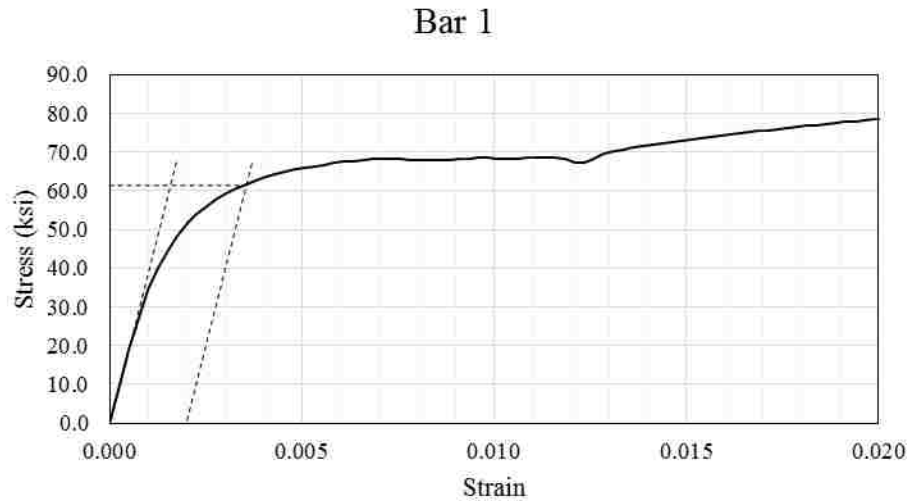


Figure A - 1. Stress-Strain Curve for Reinforcement Test 1

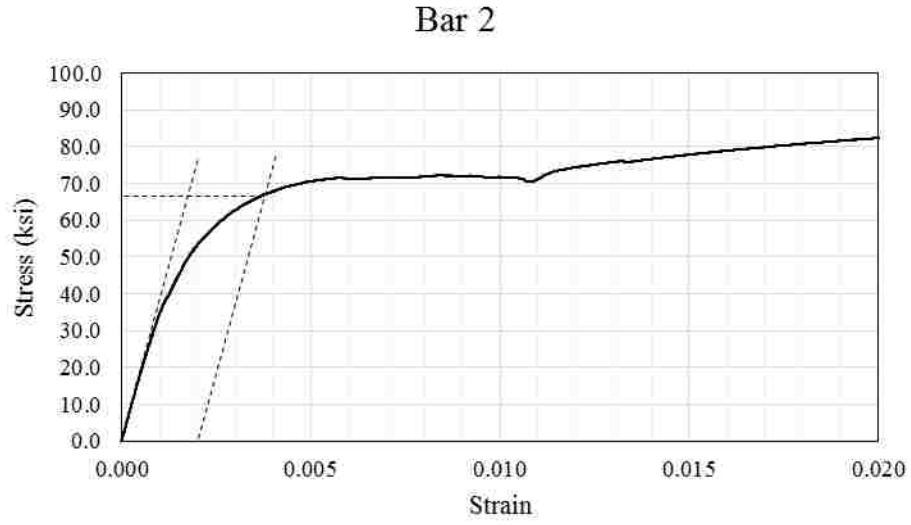


Figure A - 3. Stress-Strain Curve for Reinforcement Test 2

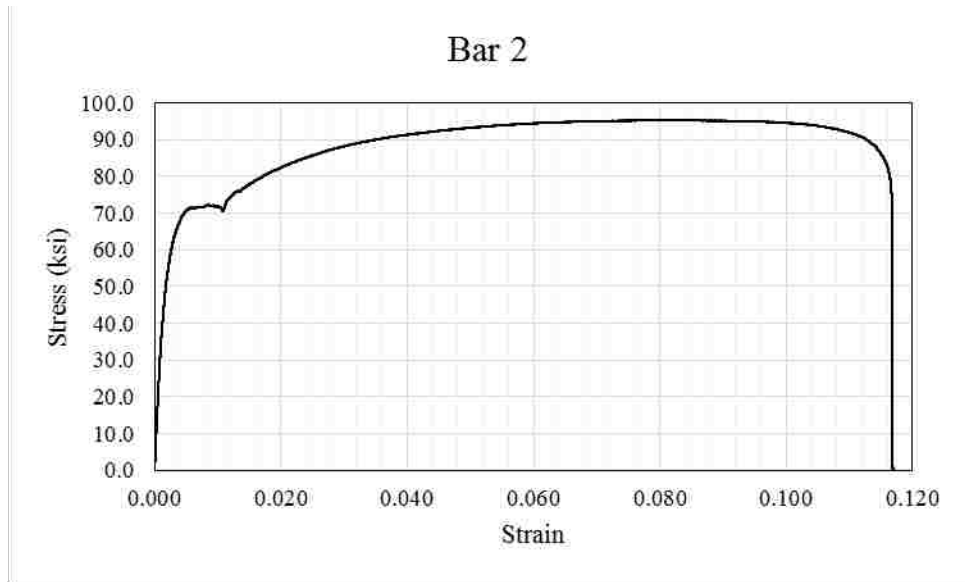


Figure A - 2. Stress-Strain Curve for Reinforcement Test 2 Showing Ultimate Tensile Strength

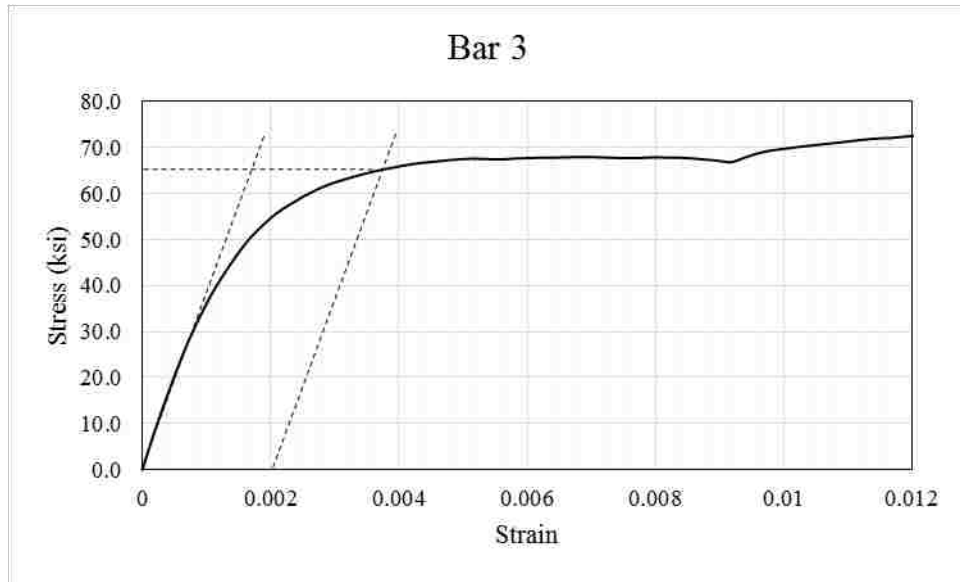


Figure A - 4. Stress-Strain Curve for Reinforcement Test 3

Table A - 7. Mortar Flow and Compressive Strength Test Results

Batch ID	Flow (%)	Cube No.	Compressive Strength (psi)
A	108	1	2320
		2	1740
		3	2300
		Average	2120
B	105	1	1990
		2	2200
		3	2280
		Average	2160
C	106	1	2090
		2	2240
		3	2130
		Average	2150

APPENDIX B. SPECIMEN PHOTOGRAPHS



Figure B - 1. Failure Mode of Typical Mortar Cube (8/27/15) @ 28-day Failure

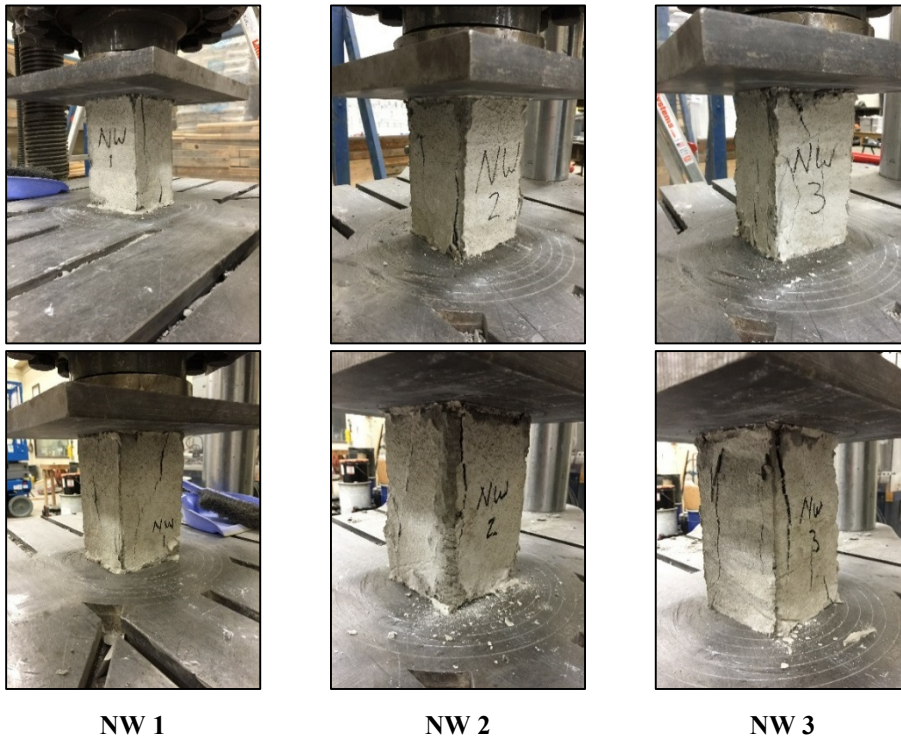
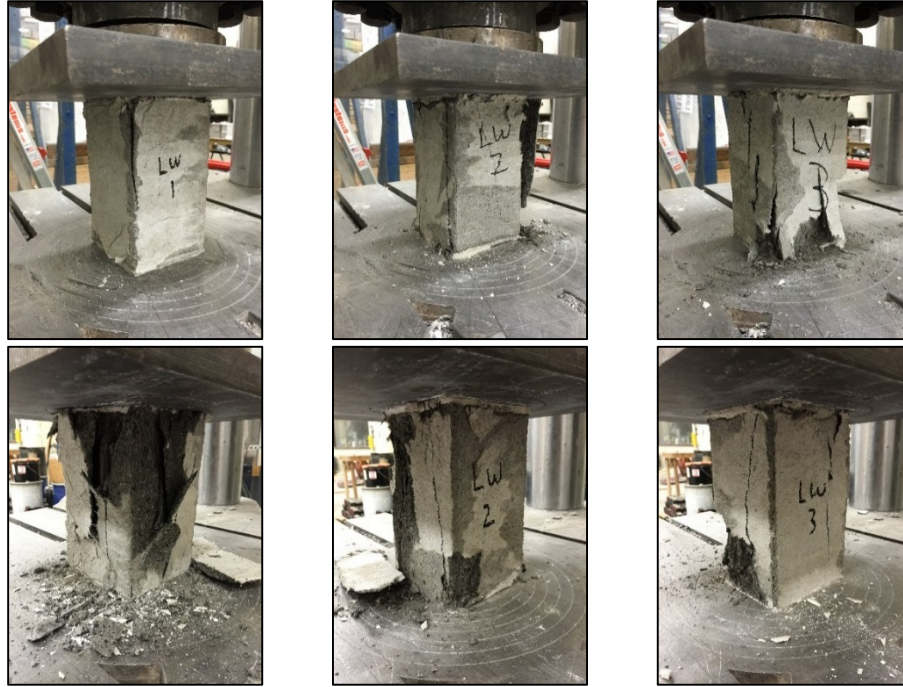


Figure B - 2. NW Grout Prisms (9/10/15) @ 28-day Failure



LW 1

LW 2

LW 3

Figure B - 3. LW Grout Prisms (9/10/15) @ 28-day Failure



NW 1

NW 2

LW 1

LW 2

Figure B - 4. NW and LW Masonry Prisms (9/10/15) @ 28-day Failure



Hollow 1(a)



Hollow 1(b)

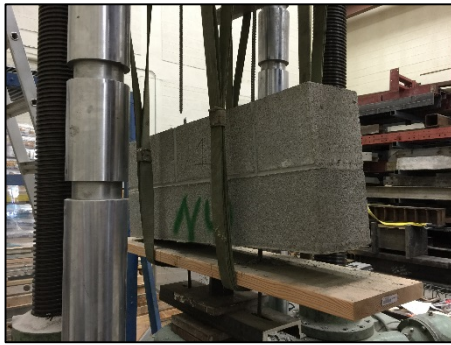
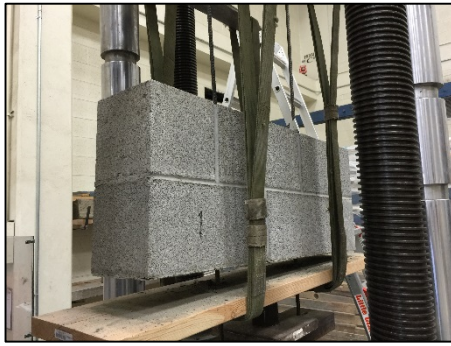


Hollow 2(a)



Hollow 2(b)

Figure B - 5. Hollow Masonry Prisms (9/10/15) @ 28-day Failure

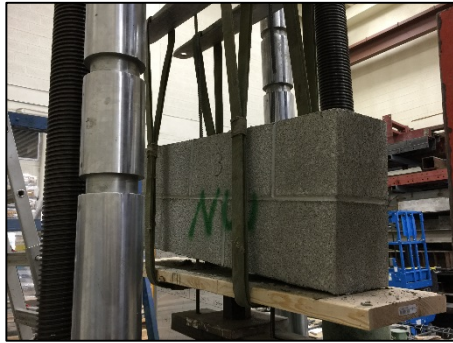


Wallette 1



Wallette 2

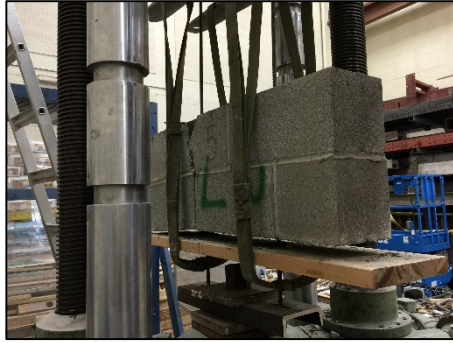
Figure B - 6. Wallette Specimens 1 & 2 (9/1/15) @ 28-day Failure



Wallette 3

Wallette 4

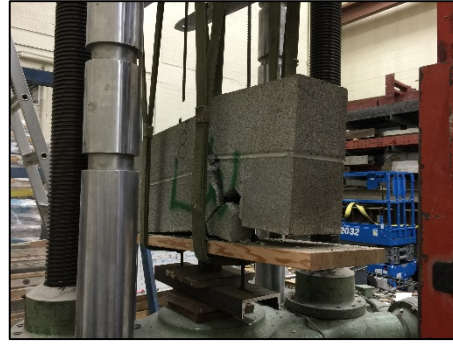
Figure B - 7. Wallettes Specimens 3 & 4 (9/1/15) @ 28-day Failure



Wallette 5

Wallette 6

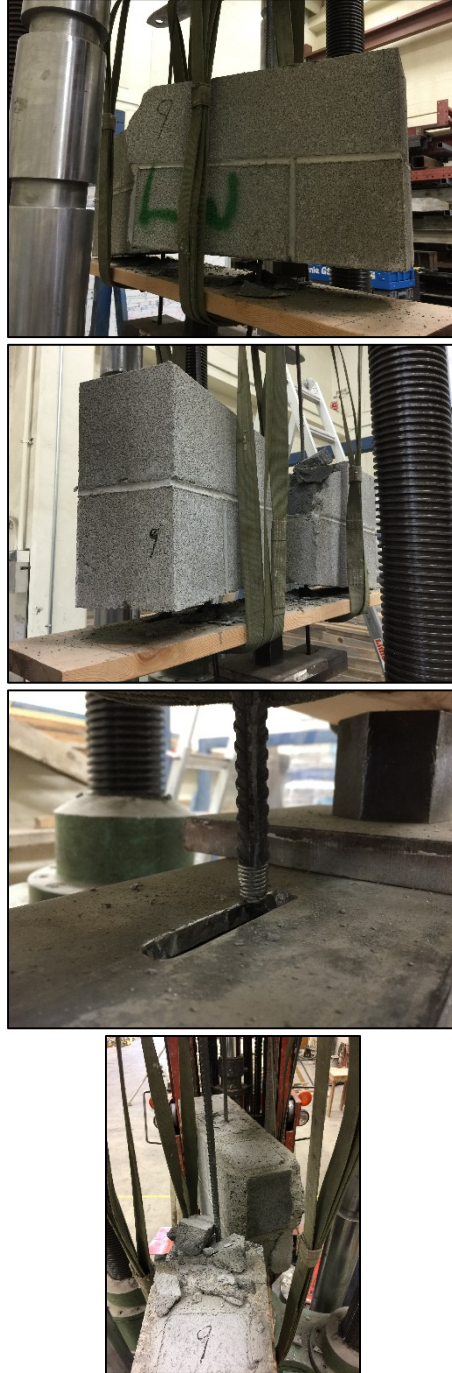
Figure B - 8. Wallette Specimens 5 & 6 (9/2/2015) @ 28-day Failure



Wallette 7

Wallette 8

Figure B - 9. Wallette Specimens 7 & 8 (9/2/15) @ 28-day Failure



Walette 9

Figure B - 10. Wallethes Specimens 9 (9/3/2015) @ 28-day Failure