2011-12-09

Strength of Concrete Masonry Prisms Constructed with Non-Traditional Grout and Type-M Mortar

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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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December 2011

ABSTRACT

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The Concrete Masonry Association of California and Nevada in conjunction with Brigham Young University devised a masonry prism testing scheme to aid in the determination of whether prisms constructed with grouts possessing high levels of supplemental cementitious materials could meet minimum masonry compressive strength requirements. ASTM standards, identical to that of concrete, place restrictions on quantities, by weight, of supplemental materials that can replace ordinary Portland cement. For an all fly ash replacement, up to 40% of Portland cement can be replaced while up to 70% can be replaced by a fly ash-slag combination. Research is focused on class F fly ash and ground granulated blast furnace slag replacing Portland cement in larger quantities. Manufacturing grouts with increasing incremental amounts help to establish higher use limitations associated specifically with masonry grout. Masonry prisms, concrete masonry units, type M mortar, and variations of grout were tested for their respective compressive strengths at age intervals of 14, 28, 42, 56, and 90 days. Grouts were designed to support the discussion of whether non-traditional grouts can achieve acceptable masonry compressive strength in prisms while not possessing adequate grout compressive strength.

The control grout consisted of one mix design containing a cementitious materials content of 100% Portland cement. Three grouts replaced Portland cement with fly ash and three grouts replaced Portland cement with a fly ash-slag combination without modifying the cementitious material weight contribution. Class F fly ash replaced Portland cement at rates of 45%, 55%, and 65%. Class F fly ash-ground granulated blast furnace slag combinations replaced Portland cement at rates of 65%, 75%, and 85% where the combinations consisted of 25% fly ash and 40%, 50%, and 60% slag.

Results indicate that all prisms exceeded the 10.3 MPa (1500 psi) minimum compressive strength requirements before the mandated 28-day age period. Neither 55% and 65% fly ash replacements nor the 85% fly ash-slag combination achieved grout strength minimums at the typical specified age. The grout mixtures manufactured with exceeding addition rates which attained greater than the minimum strength at the 28-day age were the 45% fly ash and 65% and 75% fly ash-slag combination. All grouts did, eventually, extend their strength gain beyond 13.8 MPa (2000 psi) through the course of testing and all but 65% fly ash achieved this strength within 42 days.

Keywords: masonry, prisms, compressive strength, grout, slag, fly ash

ACKNOWLEDGEMENTS

Much credit is due to Dr. Fernando S. Fonseca for his guidance and assistance not only in the evolution of this research but also in my academic progression. If it were not for Dr. Paul W. Richards and his genuine interest in the success of his students I do not believe I would have had the opportunity to attend BYU. The backing of this project was provided by Kurt Siggard of the Concrete Masonry Association of California and Nevada. This research would not have been possible without the support of the various donors: Paul Jahn from Ash Grove Packaging; Rick Child from Child Enterprises; Kevin Hatfield from Doyle Hatfield Masonry; Jim Johnson and Chris Bedford from Headwaters; Heath Holdaway from IMS Masonry; Rob Shogren and Todd Sherman from Lafarge; Wade Ficklin, Paul Kamnikar and Gerald Travis from Oldcastle; Scott Hanks and Tyler Clark from Quikrete, and Brent Overson from the Utah Masonry Council. Much appreciation is due to the National Concrete Masonry Association and D. Alan Firmage for providing scholarship monies. BYU graduate students Jacob Ballard, Juan Manuel Salguero Mendizabel, and Tana Uyema, undergraduates Robert Godfrey and Zifan Guo, as well as BYU staff David Anderson, Rodney Mayo, and David Wilson are acknowledged for their substantial assistance with specimen casting and testing. Brice Somers, also a BYU graduate student associated with the project, offered significant aid, insight, and refuge during the experimenting and writing stages of the research. Great encouragement and confidence provided by my father Steve, mother Sheri, and brother Shane was essential. Most importantly, I thank my fiancée Jessica for her support and understanding of my educational pursuits.

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1 Introduction

1.1 Fundamentals

This section explores the fundamental terms and concepts necessary for comprehension of this research. For those unfamiliar with masonry and the testing of masonry this section can provide for general understanding with brief explanations.

Masonry construction uses a variety of components for the development of masonry structures. Common components are masonry units, mortar, and grout, as well as reinforcing steel. The strength of masonry structures relies on the interactions between these components.

Masonry units can be me made from a variety of materials. The masonry units used in this thesis are Concrete Masonry Units, referred to as CMUs, composed of Portland cement, aggregate, and water. Portland cement is a hydraulic cement composed of pulverized clay and lime-bearing minerals where properties such as setting time and final strength depend on proportional composition [1]. The masonry concrete has a rapid curing process performed by exposing the blocks to high pressured steam in an autoclave. Concrete masonry, like other concrete products, performs well under vertical axial loading. A masonry unit commonly has voids or cells cut into them. These voids are often filled will grout and reinforcement for shear and tensile capacity.

Mortar, composed in proportions of cement, lime, and sand, serves to bond individual masonry units into a composite assemblage allowing for simplicity in construction and dimensional tolerance [2]. In North America mortar types M, S, N, O, and K have been adopted. Each type varies in their use depending on material properties desired for a given application. It is necessary for mortar to be workable in its plastic state. Good workability is generally established by a mason's experience and judgment. A workable mortar should both adhere to a trowel and slide off easily, spread, adhere to vertical surfaces, squeeze out of joints, and be struck of cleanly [2]. In a masonry system mortar compressive strength and bonding with the CMUs are important. The bond is formed mechanically and chemically. The thickness of the mortar affects the strength of the bond and the strength of the bond affects the compressive strength of the system. In laboratory testing the thickness of the mortar joint is held to a standardized height. Upon relating the strength of these interactions to the compressive strength of masonry, the block moisture content is, at the time of construction, the most important factor on resultant bond strength [3]. If the CMUs absorb too much water from the mortar, the mortar will stiffen rapidly resulting in poor bond; poor bond strength leads to masonry prism bond failure resulting in low compressive strengths [3].

Grout for masonry construction is a high slump mixture of cementitious materials and aggregate which can set and harden as a hydraulic cement in the presence of water [2, 4]. Cementitious materials are adhesive and cohesive, bonding mineral fragments into a solid mass [4]. Aggregates are graded by size, fine and coarse. When both classifications of aggregates are used in the grout it is deemed a type of coarse grout. Aggregate occupies the largest percentage of the volume of the grout where the strength of the aggregate greatly affects the strength of the grout [2]. The compressive strength of the grout is important for both quality control and the strength of the masonry system. In this thesis the cement content of the grout is adjusted by replacing Portland cement with supplemental cementitious materials. The two forms of supplemental cementitious materials used are Class F fly ash (FA) and ground granulated blast furnace slag (GGBS).

Fly ash is a pozzolan, which is a finely divided siliceous or siliceous and aluminous material that possesses little or no inherent cementitious property, but in the powdery form and in the presence of moisture, will chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [4]. Fly ash is a byproduct of the coal industry termed a waste material predominantly generated in the production of electricity; Class F fly ash is the product of burning bituminous and anthracite class coal [5]. The greatest utilization for fly ash is as an additive to concrete. Benefits stemming from the use of fly ash are a decrease in water demand, improvement in particle size packing, savings of Portland cement material resulting in lower costs, corrosion resistance and greater strength [5]. The strength development, however, is not as quick initially as an all-Portland cement based grout. Grout containing fly ash can often meet the strength requirements but not curing requirements.

Ground granulated blast furnace slag is increasingly being used to replace some of the cement used in concrete [6]. GGBS is a byproduct of the iron industry, where molten slag from the blast furnace is rapidly cooled and dried to form a granulate which is then ground to a fineness similar to that of Portland cement [6]. While this material is no more expensive than Portland cement, additional environmental costs are alleviated through the reduction in Portland cement's use of an extensive production process as well as GGBS's lifespan due to its own durability [6]. Being a cementitious material, it actively adds to the strength gain of the grout and significant quantities of the Portland cement can be exchanged [6]. Due to slag's small particle size, the workability of grout can be improved with its addition to the grout mix. GGBS cures more slowly and gains strength over longer periods of time which can result in lower initial strengths and higher ultimate strengths. Strength is very much dependent on the GGBS to

Portland cement proportioning where rate of hydration and ability to hydrate limit GGBS use. Alike to fly ash, curing criterion is of issue.

The quality of masonry is usually described by the compressive strength. CMUs, mortar, grout and the assemblages constructed with these components are compression tested in this research. The American Society for Testing and Materials (ASTM) provides standardized test methods for compression testing these specimen types. In terms of saving time and money during design and construction it is desirable to ensure that specified properties of masonry assemblages are satisfied using simple, economical tests [2]. Testing of masonry assemblages, called prisms, is far more economical and practical than full-scale testing. Masonry prisms are constructed with CMUs, mortar, and often grout. The specified compressive strength of masonry is represented as f'_m, which is specified by an engineer and used throughout masonry design procedures. This strength has upper and lower bounds dictated by the *Building Code Requirements and Specification for Masonry Structures*, referred to as the code. When prisms are used to verify that f'_m is achieved, specimens are compression tested and results must be greater than the value specified and less than the code's maximum value.

1.2 Motivation

The masonry industry has used supplemental cementitious materials to replace ordinary Portland cement in masonry units, mortars, and grouts. Replacing Portland cement can have economic and environmental benefits. Two common forms of recycled supplemental cementitious materials are pozzolans and slags. Extensive information is available for concrete masonry units and mortars that have included pozzolans and slags [7, 8]. Only limited data exists for masonry grouts that contain these materials. Furthering research can help to mainstream the use of supplemental cementitious materials as replacements to Portland cement in masonry grout.

Currently ASTM Standards regulate the use of supplemental cementitious materials in masonry grout. Replacement guidelines and restrictions for supplemental cementitious materials are analogous to limitations of blended hydraulic cement. Since masonry grout is a form of blended hydraulic cement, the recognition that there are differences in the uses of the end product can permit for exploration of the percentage limitations on masonry grout's Portland cement replacement.

The Concrete Masonry Association for California and Nevada (CMACN) commissioned compression testing of masonry grouts containing various Portland cement replacements rates with supplementary cementitious materials which was carried out by Twining Laboratories [9, 10]. Twining Laboratories used binary grouts with the cementitious components of Class F fly ash and Portland cement as well as ternary blends with cementitious components of ground granulated blast furnace slag, Class F fly ash, and Portland cement. These forms of grout are deemed non-traditional. By incrementally increasing the percentage of Portland cement replaced, these compression tests helped to establish new potential boundaries for binary and ternary grout blends.

There are many materials standards associated with masonry construction. Included in these standards are the compressive strengths of Concrete Masonry Units, mortar, and grout. The grouts tested by Twining Laboratories were compared against the masonry code and the ASTM strength requirements. The code relies heavily on the specified compressive strength of masonry which is a composite strength of the masonry system. Since Twining Laboratories only tested grout, it is necessary to determine if the masonry system with these grouts can achieve compressive strength minimums.

In order to guarantee that f'_m is achieved, an engineer can rely on either of two methods: the unit strength method or the prism test method [11]. The unit strength method uses proven sufficient tables in the masonry code in order to guarantee strength. By specifying a compressive strength of the individual CMU, mortar, and grout, a specified compressive strength of the masonry can be guaranteed. The combinations of strengths of the CMUs, mortar, and grout from the design tables can assure the engineer that f'_m will be achieved. The prism test method is outlined in ASTM Standard C1314. In this method, masonry prisms, composed of at least two courses of CMUs, mortar, and grout, are constructed and compression tested to determine strength [12]. The mean compressive strength of a set of three prisms must meet f'_m [12].

The unit strength method does not allow for the use of supplementary cementitious materials in the grout mix design. To verify that non-traditional grouts can be used in masonry systems prism testing is performed. Strength requirements specified by both the code and the ASTM Standards set 28-day strength criteria for masonry prisms and grout [11, 12]. Various scenarios can result from the testing of non-traditional grouts and prisms constructed with non-traditional grouts. Non-traditional grouts and grouted prisms can have either ASTM compliant or non-compliant addition rates of cementitious materials as well as compliant or non-compliant compressive strengths. The non-traditional grouts and prisms may or may not meet strength requirements by the 28-day age.

Conclusions about whether it is plausible to increase the ASTM Portland cement replacement rates for masonry grout depend on compressive strengths and curing ages when strengths are achieved. Greater quantities of recycled cementitious materials supplementing the Portland cement content in masonry grouts promotes and brands masonry construction as cost and planet conscious. Intent is to provide engineers with additional means to create sustainable concrete masonry structures by promoting broader supplemental cementitious material addition rates for masonry grout and by extending discretion to engineers in lengthening the minimum curing ages, which could further increase allowable addition rates.

1.3 Scope

The compressive strengths of masonry prisms constructed with non-traditional grouts are determined. CMUs, mortar, and grout being components of masonry prisms are tested individually to assure ASTM compliancy and to attribute prism strength gain appropriately. Selection of materials is based on those commonly used in masonry construction in California, Utah, and Nevada. Since concretes with pozzolanic or slag material gain strength over longer periods of time specimens are compression tested at age intervals of 14, 28, 42, 56, and 90 days to determine the curing age at which compressive strength minimums are achieved [4, 13].

The types of CMUs and mortar remain constant throughout experimentation focusing the testing on the performance of the non-traditional grout and prism specimens. Seven variations of grout are manufactured. An all Type I/II Portland cement based grout is used as a control. This grout is designed to mimic those used in the Twining Laboratories grout testing for the benefit of comparison. Binary grouts are composed of Type I/II Portland cement and Class F fly ash. The Portland cement content is replaced by 45%, 55%, and 65% FA. Ternary grouts are composed of Type I/II Portland cement, Class F fly ash, and ground granulated blast furnace slag. The Portland cement content is replaced with 25% FA and 40%, 50%, and 60% GGBS for total replacements of 65%, 75%, and 85%. All of the binary grout blends exceed the addition rate of 40% allowed by the ASTM. Ternary grouts are limited to 70% Portland cement replacement; 75% and 85% replacements exceed this standard. These non-traditional grout variations have different replacement rates than those tested by Twining Laboratories for the purpose of extending the available data set. Eight variations of masonry prisms are constructed and compression tested; seven of the variations are fully grouted using each of the grouts detailed above alongside hollow/ungrouted prisms.

Since a majority of grout and prism specimens defy the current standard, boundaries of masonry grout's Portland cement replacement with fly ash and fly ash-slag combinations are tried. This testing scheme limits the pozzolan to Class F fly ash and the slag to GGBS. Further, the replacement rate with FA in the ternary blend is held constant. These conditions set another step towards extending the current masonry grout Portland cement replacement rates. Testing cannot encompass all of the supplemental cementitious materials and percentage combinations available. Results are also based solely on the compression test since this is the most prominent material property used in masonry design. Certainly there are other properties important to consider in masonry construction. By validating compressive strength results first, further testing for the acceptability of additional material properties is then justifiable.

1.4 Outline of this Thesis

This thesis contains five chapters. Chapter 1 is an introductory chapter included to profile the research. Chapter 2 provides research background information. Materials selection, grout design, specimen construction and testing methods are discussed and explained in Chapter 3. Results of the testing scheme are presented in Chapter 4 while Chapter 5 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.

2.1.1 Class F Fly Ash and Ground Granulated Blast Furnace Slag

The Federal Highway Administration has accumulated vast quantities of concrete related research. Their accrual has developed substantial resources and information on the use of fly ash and ground granulated blast furnace slag. Pozzolans, such as fly ash, and slags, such as ground granulated blast furnace slag, which have been utilized as Portland cement replacement materials in the United States since the early 1930's, can dramatically reduce the materials cost of masonry structures [13, 14]. The Administration encourages the implementation of fly ash when the price of fly ash concrete is less than or equal to the price of mixes with only Portland cement [14]. Use of FA and GGBS generally improves workability which is of great concern in masonry grout. Concretes containing Class F fly ash can develop lower strengths while slag concretes can exceed the strength of all Portland cement concretes [13, 14]. Strength development for concretes with FA and GGBS is prolonged and influenced by the quantities incorporated. The Federal Highway Administration suggests that substitution rates for FA be limited to less than 25% and for GGBS to be limited to 50%.

2.1.2 Compression Testing of Masonry Prisms

Robert G. Drysdale and Ahmad A. Ahmad have conducted significant research in the masonry field. In *Behavior of Concrete Block Masonry Under Axial Compression* they have provided insight on the best methods for obtaining the compressive strength of masonry. They tested both full block prisms and half block prisms to determine the masonry's reliance on the block size. Results indicate that using half blocks were essentially identical to the results for full block prisms [15]. Block sizes in laboratory testing can be smaller than those used in real construction and still provide accurate results.

The compressive strength of masonry relies on the interactions between the components in the system. Their extensive examination on the interaction of the components when axially loaded concludes on the effects of the strengths of individual components. They have determined that the compressive strength of fully grouted masonry relies less on the mortar joint; doubling the mortar joint thickness decreased their compressive strengths by 16% for hollow prisms and 3% for grouted prisms.[15]. Small variations in mortar joint thickness can be less strictly controlled. By testing various mortar strengths they conclude that the strength of the mortar did not play a major role in the compressive strength development [15]. Choice of mortar type should then not play a role in the compressive strength of this thesis's grouted prisms, however E.H. Fahmy and T.G.M. Ghoneim found that for both ungrouted and grouted prisms the prism strength increased with increasing mortar strength [16]. From the Drysdale tests, grout did not contribute proportionally to the prism strength and it became apparent that significantly increasing the strength of the grout only slightly increased prism capacity [15]. Minimum strengths of the grout are then the primary focus. Fahmy and Ghoneim reveal in their conclusions on the behavior of concrete block masonry that the prism strengths increase with block strength; fully grouted prisms have less of an increase in strength than hollow prisms [16].

When comparing the methods of establishing compressive strength, Drysdale and Ahmad found that the testing of two course high prisms do not correlate well with the behavior of masonry walls [15]. Their results are confirmed by A.H.P Maurenbrecher's masonry test procedures analysis where lower height-to-thickness ratios result in stronger prisms [17]. Much of the developed and implemented procedures for testing concrete masonry use prisms with height-to-thickness ratios of 2. With half scale blocks this can be achieved with two masonry prims without the use of a correction factor. Maurenbrecher used stress rates for loading where slower load rates gave only slight reductions in strength [17]. Mean strength is used in a majority of the prism test research encountered and in laboratory testing of constructed masonry for strength verification. Maurenbrecher discusses the mean strength and characteristic strength. Obtaining characteristic strengths are recommend by testing a minimum of ten replicate specimens to give reasonably reliable results [17].

2.1.3 Relevant Requirements For Grout and Masonry

The compressive strength of masonry, as a result of the prism test method, must either exceed or be equal to 10.3 MPa (1,500 psi) but be no greater than 27.6 MPa (4,000 psi) for concrete masonry in order to be used as a nominal strength value [11]. Utilizing the prism test method for the verification of f'_m, ASTM International specifies that grout for masonry must obtain a minimum compressive strength of 13.8 MPa (2000 psi) at 28 days [18]. The masonry code indicates that the specified compressive strength of grout (f'_g) shall exceed or be equal to the compressive strength of masonry while not exceeding 34.5 MPa (5000 psi) [11]. 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 governed by more than just compressive strength; Sections 3.1.1.5 and 3.1.1.6

of ASTM C476 restrict fly ash and slag use by referring to ASTM C595/C595M. This points to the Standard Specification for Blended Hydraulic Cements limiting the maximum pozzolan content to 40% by mass of the blended cement and the total content of pozzolan and granulated blast furnace slag to less than 70% by mass of the blended cement [19]. These addition rates are significantly higher than those suggested by the Federal Highway Administration.

2.2 Related Work

As previously mentioned, CMACN began experimentation in conjunction with Twining Laboratories to test the boundaries of masonry grout when Portland cement is replaced in large percentages by fly ash or a combination of fly ash and ground granulated blast furnace slag beyond the limits of the ASTM Standard. Trial batches composed of a standardized 100% Portland cement grout design, modified binary grouts with FA replacing Portland cement at 20%, 30%, 40%, 50%, and 60%, as well as grouts with FA and GGBS at 50%, 60%, 70%, and 80% replacement of Portland cement were created. The fly ash in the ternary blend was held at 25% of the weight of the standardized Portland cement material. Specimen creation followed ASTM C1019 where minor deviations occurred including sample fabrication within CMU cores and diamond saw-cutting of CMUs to obtain the specimens one day prior to testing.

Results of the compression testing performed on these grout samples are shown in Table 2-1. The ASTM for the Standard Specification for Grout for Masonry C476 Section 4.2.2.1, indicating that grout shall have a compressive strength of 14 MPa (2000 psi) at 28 days, was easily satisfied by all grout samples, except 60% FA Replacement [9, 18]. However, it is important to note that the 60% FA Replacement grout is a grout capable of withstanding a stress greater than 14 MPa (2000 psi) when more time for strength gain is allotted. Beyond an age of 56 days all grouts in this scheme have adequate strength.

As a result of the ASTM C595 specifications, the grouts containing 50% and 60% FA Replacement and 80% FA & GGBS Replacement are not suitable for use as masonry grouts. While more extensive testing, such as experimenting with flexure and tension limitations, may be necessary, the 50% FA Replacement and 80% FA & GGBS Replacement grouts meet the axially loaded compressive strength requirements. With confirmation that these currently prohibited grout mixtures are conservatively represented in the various *Building Code Requirements and Specification for Masonry Structures* equations where the specified compressive strength of masonry is used, separating the ASTM limitations on masonry grout from all other forms of blended hydraulic cement is plausible [11]. Addition rates of pozzolanic and slag materials under a separate masonry grout ASTM could be increased and a distinction between masonry grout and typical blended hydraulic cement can be made. While Twining Laboratories and the efforts of this thesis further the investigation of the legitimate use of the various forms of non-traditional, non-code compliant grouts for masonry construction, the experimental results obtained from these studies do not solely possess enough information to alter high-percentage replacement of Portland cement limitations or age restrictions on masonry grout; it does, however, provide adequate data that can allow for reassessment of the standards in place pending further analyses and assumption of risk.

Table 2-1: Twining Laboratories Grout Specimen Compressional Strength Data Summary

Age	100% Portland Cement	20% FA Replacement	30% FA Replacement	40% FA Replacement	50% FA Replacement	60% FA Replacement	50% FA & GGBFS Replacement	60% FA & GGBFS Replacement	70% FA & GGBFS Replacement	80% FA & GGBFS Replacement
days	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
7	20.6	19.2	16.9	10.6	11.1	6.3	13.0	15.6	13.4	10.1
14	22.6	20.1	20.5	14.8	14.4	7.9	19.9	22.5	19.1	13.4
28	28.0	22.8	26.4	18.5	19.9	9.9	22.8	22.3	23.5	16.8
42	28.8	26.2	26.8	21.0	21.6	13.3	25.2	31.3	29.0	18.7
56	29.6	29.3	32.1	23.0	20.4	14.3	34.5	33.3	29.4	21.6
180	28.4	35.7	39.1	32.3	29.9	26.1	42.8	41.4	36.3	24.8

3 Experimental Methodology

3.1 Overview

The following sections include details describing the selection and use of materials in regards to the manufacturing of grout as well as construction of the masonry prisms and component samples. Descriptions of the test method standards as well as explanations for deviations from those standards are incorporated. A portion of data and tests results relevant to materials detailed in this section are presented.

3.2 Materials Selection

Selection of certain materials was based on the CMACN's used materials for the high replacement grout study for the benefit of a direct comparison with this research. CMACN was responsible for the ordering and coordination of the delivery of determined quantities of CMUs, mortar, sand, pea gravel, Portland cement, fly ash, ground granulated blast furnace slag and Hydrocal. All water used in mortar, grout, and Hydrocal mixing was from a potable source.

3.2.1 Concrete Masonry Units

The concrete masonry units used in this study were manufactured from the same batch using consistent fabrication methods. The ASTM C90 compliant units were made by Oldcastle in Utah and arrived at the laboratory on pallets. These units were formed in molds and thus have tapered cells which aid in the de-molding process. The tapered cells create face shells/webs that vary slightly in dimension from top to bottom. Units were of a 200x200x200 mm (8x8x8 inch) nominal size with one cell. Justification of the use of these half size concrete masonry units comes as it reduces the height-to-thickness ratio over larger block sizes as well as reduces the testing apparatus' necessary loading capacity and the assemblages' overall size and weight. CMUs and prisms constructed from these CMUs are able to fit the on-site loading machine as well as provide for easier maneuverability, reduced space consumption, and decreased physical labor in the laboratory environment. The CMUs' actual dimensions need be determined separately from prisms as allowances for manufacturing tolerances and inconsistencies of a standard of 10 mm (0.375 inch) mortar joint alter recorded prism dimensions. Following the Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units ASTM Standard C140, six representative units were selected for determination of absorption, in-situ moisture content before sample construction, density, and measurement of dimensions. Table 3-1 summarizes averaged dimensions. While ASTM C140 Annex A1.2.2 instructs the measurer to disregard grooves, the dimensions of the grooves were measured separately in order to later account for the loss of bearing area used in determining compressive strength [20].

The dimensions, as shown in Table 3-1, were utilized in the calculation of the pertinent surface areas summarized in Table 3-2. CMU standardized measuring can account for the bearing areas of multiple specimen forms including CMUs and both hollow and grouted prisms. The average grouted bearing area refers to the area that the unit would occupy if it were grouted omitting the groove. Omission of the area loss due to the groove is not required in area determination and contributes to less than 4 cm^2 (0.5 in^2) of standard described area. Figure 3-1 pictures the groove of the concrete masonry unit. The average hollow/ungrouted bearing area refers to the area the CMU surface occupies, again, omitting the groove. The hollow/ungrouted bearing area is used when calculating the stress from loads on CMUs and hollow prisms.

Table 3-1: CMU Standardized Dimensions

Dimension	Unit	
	mm	in
Average Groove Dimension	19.1	0.8
Average Height (H) at Mid-Length/ Mid-Width	193.4	7.6
Average Length (L)/ Width (W) at Mid-Height	194.5	7.7
Average Web (t_w) Thickness	33.5	1.3
Average Face Shell (t_{fs}) Thickness	46.2	1.8

Table 3-2: Averaged CMU Related Areas

Area Type	Unit	
	mm^2	in^2
Average Hollow/ Ungrouted Bearing Area	2445.1	37.9
Average Grouted Bearing Area	3748.0	58.1

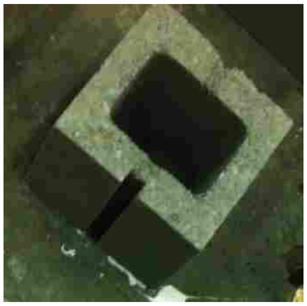


Figure 3-1: CMU Groove

Using the aforementioned ASTM Standard, Table 3-3 displays the resulting averaged CMU absorption, density, and moisture content for both lab measured and manufacturer provided values. The provided values were obtained from the data sheet found in Appendix C Figure C-6. The values presented in this figure are for CMUs of different dimensions but of the same mix design and casting methods and are included for completeness. The measured average moisture content is obtained by subtracting the average rate of moisture absorbed by the block in Appendix A Table A-3 from 100% for easy comparison. Absorption and moisture content affect the interaction between freshly laid mortar or freshly poured grout and the concrete masonry unit [11]. Absorption testing of the required six units can be seen in Figure 3-2. These measurements can help account for the factors that can affect compressive strength to make reasonable relationships to strength loss should it occur.

Table 3-3: Average CMU Absorption, Density, and Moisture Content

Average Absorption						Average Density				Average Moisture Content	
Measured			Provided			Measured		Provided		Measured	Provided
g/cm^3	pcf	%	g/cm^3	pcf	%	g/cm^3	pcf	g/cm^3	pcf	%	%
0.13	8.40	6.60	0.15	9.67	8.76	2.05	128.21	1.77	110.39	43.01	56.51

Figure 3-2: CMU Absorption Testing

3.2.2 Type M Mortar

Commercial Grade Quikrete Mason Mix Type M Mortar was selected as the mortar for use in this particular series of masonry prisms constructed with non-traditional grouts. Common mortar types N and S were researched simultaneously, however, separate from this record. These three mortar types represent mortars used frequently in the masonry construction industry, especially in the California, Nevada, and Utah regions. The mix is a standard formulation of a dry pre-blended mixture of sand and cements meeting ASTMs C270, C387, and C1714 arriving on a pallet in 36.3 kg. (80 lb) bags requiring only proper amounts of water and mixing for use [21]. Type M mortar has the highest volume proportion of cement [22]. While this mortar type is generally the least workable in its plastic state, its hardened state is generally the strongest in compression and tension where the manufacturer details a compressive strength of 17.2 MPa (2500 psi) [21, 22]. Mortar is utilized in the prism and mortar cube specimens.

3.2.3 Grout

Materials exhibiting cementitious properties used in experimentation are Type I/II Portland cement, Class F fly ash, and ground granulated blast furnace slag. A Type I/II Portland cement is used in ordinary construction where either special properties are not required or when moderate sulfate resistance or moderate heat of hydration is desired [4]. The non-traditional forms of grout found in this study are composed of increased amounts of fly ash and ground granulated blast furnace slag, which gradually replace the Portland cement content while maintaining a constant cementitious material weight percentage. Portland cement type, fly ash class, and slag type were chosen after reference to previous CMACN grout-only tests. Chemical and physical analysis results of the FA and GGBS are presented in Appendix C. While grout cementitious proportioning changed to expand the data set and hone in on an addition rate threshold, materials used in those proportions remained the same.

A coarse grout is employed; aggregates used in the formulation of the grouts were fine and coarse grained. Fine aggregate, in this case sand, must pass through a 9.5 mm (0.375 inch) diameter sieve; coarse aggregate is larger than this restriction [23]. The coarse aggregate used is a pea gravel of a 10 mm (0.375 inch) diameter size as specified to which 100% passes a 12.5 mm sieve (0.5 inch) [23]. Reports of the physical properties of both the sand and the gravel used are presented in Appendix C. The results of the sieve analysis performed by Geneva Rock Products, Inc. are shown in Table 3-4. Aggregates were tested for absorption and in-situ moisture content just prior to grout mixing. The test for coarse aggregate absorption was completed via ASTM C127 and fine aggregate absorption was completed via ASTM C128. The absorptions reported and used in obtaining the free water content of the grout mixes are the absorptions reported by Geneva Rock Products, Inc. The results of the moisture content testing as well as the reported absorptions are presented in Table 3-5.

Table 3-4: Aggregate Gradation

(a) Sand Gradation

Sieve Size		Percent Passing
mm	No.	%
4.750	4	100
2.360	8	94
2.000	10	85
1.180	16	61
0.600	30	37
0.425	40	30
0.300	50	20
0.150	100	6.4
0.075	200	1.2

(b) Gravel Gradation

Sieve Size		Percent Passing
mm	No.	%
9.500	3/8"	100
4.750	4	72
2.360	8	24
1.180	16	5
0.300	50	1.5
0.075	200	1

Table 3-5: Aggregate Absorptions and Moisture Contents

Aggregate Type	Absorption %	Moisture Content %
Sand	1.17	0.9
Gravel	0.8	0.13

3.3 Specimen Construction

This section outlines the construction of grout, mortar, and prism specimens. The American Society of Testing and Materials sets the standards used by the Masonry Standards Joint Committee (MSJC) in the *Building Code Requirements and Specification for Masonry Structures*. The ASTM standard specimen construction techniques and deviations from the standards are discussed.

3.3.1 Mortar Specimens

Mortar was prepared in a mechanical mixer; Figure 3-3 shows a mason mixing a batch of mortar in the mixer. Batch sizes and quantities of water added were at the discretion of the professional masons on hand to construct the prisms. Water levels were based on the mortar's workability and consistency. Temperature and flow of the mortar are presented in Table 3-6 below, while mortar flow measurements are presented in Appendix A Table A-4. The initial flow of mortar is a laboratory measured property of mortar that indicates the percent increase in diameter of the base of the truncated cone of mortar when it is placed on a flow table and mechanically raised 12.7 mm (0.5 inches) and dropped 25 times in 15 seconds [24]. The flow test for mortar is shown in Figure 3-4 and the measuring of temperature in Figure 3-5. The flow of mortar should reach 110 ± 5 mm during the flow test [25, 26]. The mortar flow averaged 111.8 mm for all four measurements with each measurement falling within the acceptable range.

Figure 3-3: Mixing of Mortar

Table 3-6: Mortar Temperature and Flow

Mortar Type	Temperature		Flow
	°C	°F	%
M	21.1	70	10.04

Figure 3-4: Flow Test of Mortar

Figure 3-5: Temperature Test of Mortar

ASTM C109/109M governs the test methods for mortar compressive strength specimens. Three specimens for each test age were made in compliant specimen molds creating 50 mm (2 inch) cubes of mortar. Figure 3-6 shows the release agent coating being applied to the interior faces of the mold. Mortar was poured into the compartments in two layers each approximately half of the depth of the mold and tamped to ensure uniform filling of the molds with 4 rounds of 8 strokes each at right angles to each other [27]. Mortar was leveled with the top of the mold in a sawing motion with a trowel after the second layer had been tamped [27]. Upon completion of the molding, the test specimens were placed in a moist room under a plastic sheet to prevent ponding but allowing exposure to the moist air and are shown in Figure 3-7 [27]. Specimens remained undisturbed in their molds for 72 hours after which they were removed from the mold and stored in the moist room until reaching their respective testing ages [26, 27]. The same moist room was used for both grout and mortar specimens. The final form of the specimens is shown in Figure 3-8.

Figure 3-6: Release Agent and Sealant Application to Mortar Cube Molds

Figure 3-7: Mortar Specimens in Moist Room

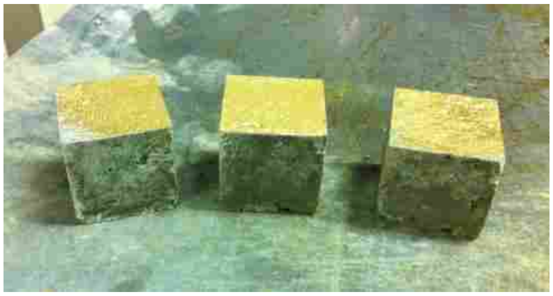


Figure 3-8: Mortar Cube Specimens

3.3.2 Grout

This section is broken up into two sub-sections. The first sub-section is focused on the composition and formulation of the grout while the second sub-section describes the casting of grout samples.

3.3.2.1 Grout Composition

The composition of the grout was proportioned by weight. Design of the all Portland cement grout closely mimics the mix design used by Twining Laboratories. A numbering and color scheme was devised to reduce the likelihood of specimen misidentification after construction. The weights of each grout constituent are summarized in Table 3-7. The quantity denoted by the superscript is a quantity that was recorded incorrectly and determined by back solving using the knowledge of when the grout design was altered. The grout design was altered in two ways, to reduce batch excess and to reduce the slumps of grout types 5-7. Designs of the grouts are still consistent; where small differences in percentages occur, rounding error of weight quantities resulted after scaling of the grout batch size to reduce excess grout making and to conserve material resources. The percentage of weight of each grout constituent, sand, gravel, water, and cementitious material is shown in Table 3-8 along with the number and color scheme for reference.

Grout materials were mixed with water on the site location. Per ASTM 476 Standard Specification for Grout for Masonry, individual cementitious materials and aggregates were first weighed and then mixed with a mechanical mixer for a minimum of five minutes with sufficient potable water to achieve the desired consistency [18]. A Concrete Titan 125E Heavy-Duty Concrete Mixer was used to make the seven variations of grout. The mechanical mixer and grout sampling are shown in Figure 3-9.

Table 3-7: Grout Constituent Weights

Grout Type	Sand		Gravel		Water Added		Water Free		Cementitious Material					
									Portland Cement		Fly Ash		Slag	
#	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb
1	872.48	1923.48	369.12	813.78	257.14	566.90	245.25	540.67	268.45	591.84	-	-	-	-
2	872.48	1923.48	369.12	813.78	257.14	566.90	245.25	540.67	147.65	325.51	120.80	266.33	-	-
3	654.36	1442.61	276.84	610.34	192.86	425.18	183.93	405.51	90.60	199.75	110.74	244.13	-	-
4	610.73	1346.44	258.39	569.65	180.00	396.83	171.67	378.47	65.77	145.00	122.15	269.29	-	-
5	610.73	1346.44	258.39	569.65	161.48	356.00*	153.15	337.64	65.77	145.00	46.98	103.57	75.17	165.72
6	641.27	1413.76	271.31	598.13	169.55	373.80	160.81	354.52	49.32	108.74	49.33	108.75	98.66	217.50
7	641.27	1413.76	271.31	598.13	169.55	373.80	160.81	354.52	29.60	65.25	49.33	108.75	118.39	261.00

* Recorded value different than value presented

Table 3-8: Grout Constituent Weight Percentages

Grout Type	Color Designation	Sand	Gravel	Water Free	Total Cementitious	Total Cementitious Composition		
						Portland Cement	Fly Ash	Slag
#		%	%	%	%	%	%	%
1	Orange	49.71	21.03	13.97	15.29	100	0	0
2	White	49.71	21.03	13.97	15.29	55	45	0
3	Red	49.71	21.03	13.97	15.29	45	55	0
4	Blue	49.71	21.03	13.97	15.29	35	65	0
5	Green	50.47	21.35	12.66	15.53	35	25	40
6	Pink	50.47	21.35	12.66	15.53	25	25	50
7	Yellow	50.47	21.35	12.66	15.53	15	25	60

Figure 3-9: Mixing and Sampling of Grout

Grout should slump between 200 to 280 mm (8 to 11 inches) [18]. With the addition of the fine particles making up FA and GGBS, slumps increase as greater percentages of these materials are added to the grout mixes. The initial amount of water added to the grout was based on the slump test. The first grout design, containing cementitious materials of 100% Portland cement, was targeted between the 200 to 280 mm slump range, with a 200 mm slump being the objective due to foreshadowed increases in slump as the grout cementitious material content was modified. The water content was held at a constant proportion for the grout types 1-4. The slump test was performed as outlined in the procedure of ASTM C143/C143M Standard Test Method for Slump of Hydraulic-Cement Concrete. Figure 3-10 shows the apparatus used in determining the grout slump. A representative sample of the grout was chosen from the batches according to ASTM C172. ASTM C172 specifies the standard practices for sampling freshly mixed concrete. In the sample selection process less than 15 minutes may pass between obtaining the first and final portions of the composite sample, with slump and temperature being recorded within 5 minutes of obtaining the final portion being careful not to obtain portions of the composite sample from the very first or last part of the batch discharge [28]. The mold was filled in three layers, each approximately one third the volume of the mold, rodding each layer 25 times uniformly over the cross section penetrating approximately 25 mm (1 inch) into the layer below [29]. The mold was removed immediately in a vertical direction, eliminating twisting motions, within 5 to 7 seconds by raising the mold 300 mm (12 inches) [29]. The slump was determined by measuring the vertical difference between the top of the mold and the displaced original center of the top surface of the specimen [29]. The temperature monitoring of the grout followed the ASTM C1064/C1064M where ASTM C172 practices of sampling were used. The temperature measuring device was positioned in a sampling container so that the end of the temperature sensing portion was submerged in at least 75 mm (3 inches) of the grout for at least

2 minutes and no longer than 5 minutes while being read to the nearest 0.5 °C (1 °F) [30]. Both the records of the slumps and temperatures of the grouts are presented in Table 3-9. All grout types were within the acceptable limits of the standard grout slumps except for grout type 4. Grout type 4, consisting of cementitious materials 35% Portland cement and 65% fly ash, was deemed flowable. The slump mold is 300 mm (12 inches) tall; slump judged as flowable refers to only minute traces of the grout and its aggregate remaining on the slump apparatus after the test. The consistency of grout type 4 with a flowable slump can be seen in Figure 3-11 (a) in comparison to grout type 5, Figure 3-11 (b), which had a slump of 200 mm (8 inches). It was decided that modifying only the water content would reduce the slumps of grout types 5-7 in comparison to type 4 and not stray from the experiment's intent. Since type 4 produced a flowable grout and types 5-7 had the same and greater addition rates of the fine particle size supplemental cementitious materials, it was inferred that subsequent slump testing would produce flowable grouts. As this was not desired, the water content was reduced until type 5 produced a 200 mm (8 in) slump.

Figure 3-10: Slump Testing Apparatus

Table 3-9: Grout Slumps and Temperatures

Grout Type #	Slump (mm)	Slump (in)	Temperature (°C)	Temperature (°F)
1	228.6	9	20.0	68
2	241.3	9.5	21.1	70
3	266.7	10.5	20.6	69
4	Flowable		20.0	68
5	203.2	8	20.6	69
6	215.9	8.5	21.1	70
7	266.7	10.5	21.1	70

(a) Grout Type 4

(b) Grout Type 5

Figure 3-11: Grout Consistency Comparison

3.3.2.2 Grout Specimens

Since the grout make-up is attributed to the prism compressive strength focus of these experiments, it is important to know the compressive strength of the grout alone. Five specimens of each grout type for each break day were made. The construction of grout specimens is detailed in ASTM C1019. As prescribed in Section 6.2 of this standard, an alternative method of forming specimens is tolerable and this option was used as this proved more resourceful. The alternative method used a single specimen shape, method of forming, masonry unit type, and grout mix per grout type being assessed [25]. A conversion factor based on comparative testing of ten pairs of specimens is used to modify the results from this alternative method and discussed further in Section 3.4.2.1 of this thesis [25].

The CMU blocks described in Section 3.2.1 above were engaged in the construction of the grout specimens. The method of filling the cores of these units was employed where the seven variations of grouts detailed in Sections 3.2.3 and 3.3.2.1 above were poured into the CMU cell. The construction of these specimens with this variant of mold simulates the in-situ construction of the masonry prisms assembled with these grouts in the CMUs. A non-absorptive plastic sheet was used a barrier between the grout specimens and the level location where the molds remained undisturbed for 48 hours [25]. The layout of the CMU grout molds is shown in Figure 3-12. Grouts used in the creation of grout specimens and the grouts used in the masonry prisms were of the same batch. The CMU cell molds were filled within 15 minutes of obtaining the final portion of the sample and filled with grout in two layers of approximately equal depth [25]. Each layer was rodded 15 times with a tamping rod; the first layer was rodded through its depth and the second layer penetrating approximately 12.7 mm (0.5 inch) into the lower layer where strokes were distributed evenly over the cross section of the mold [25]. The top surface was stuck off level with a straightedge to produce a flat surface that is even with the top edge of the mold and left to cure with a wetted cloth draped over the top surface [25]. Demonstrations of grout layering, rodding, and covering are shown in Figure 3-13.

Figure 3-12: Grout Mold Layout

Figure 3-13: Grout Specimen Creation

The CMU mold was removed from the grouted core by first saw cutting the CMU and then by striking off the face shells as depicted in Figure 3-14 and Figure 3-15. Saw cutting of the mold was done just shallow enough not to cut into the grout to make the CMU face shells easy to remove with little force. Immediately after mold removal specimens were placed in a moist room of 100% humidity at 31°C (86°F) until the day of testing; Figure 3-16 depicts grout specimens removed from their CMU molds in the moist room where they remained until capping and subsequent compression testing.

Figure 3-14: Saw Cutting of Grout Specimen Molds

Figure 3-15: Removal of Grout Specimen CMU Mold

Figure 3-16: Grout Specimens in Moist Room

3.3.3 Prism Specimens

Masonry prisms were assembled with the components of concrete masonry units, mortar, and grouts previously defined by professional masons. Two CMUs with one mortar joint either, grouted or ungrouted, make up a single masonry prism test specimen. Prisms averaged a height-to-thickness ratio of 2.06, which falls between accepted 1.3 to 5.0 ratios [12]. Procedure calls for a modification of the compressive strength based on the height-to-thickness ratio. Table 1 of ASTM 1314 indicates that a correction factor of 1.0 be used for a 2.0 ratio and 1.04 for a 2.5 ratio. Linearly interpolated the correction factor for a 2.06 ratio yields 1.0048, which is to be taken as 1.0. Component deviations from the ASTM 1314 governing compressive strength masonry prism test specimens have been explained previously. The goal in the creation of the masonry prism specimens is to be representative of those used in construction, especially in the California, Nevada, and Utah areas. Five prisms at each test age for each of the grout types 1-7 and those without grout were constructed.

Prisms were constructed in an opened, moisture-tight bag large enough to enclose and seal the completed prism on a flat and level base [12]. Units were laid in stack bond with full mortar beds and were free of surface moisture at the time of construction [12]. Masons were instructed to cut flush 10 mm (0.375 inch) mortar joints [12]. Prism construction is shown in Figure 3-17. When prisms were to be grouted, they were grouted between 24 and 48 hours following construction of the prism [12]. While waiting to be grouted prism specimens were sealed in the moisture tight bag with a zip-tie. Prisms designated as hollow/ungrouted were permanently sealed. Prior to grouting, mortar fins and droppings were removed from the prisms as shown in Figure 3-18. Grout consolidation procedures representative of those used in construction were used as demonstrated in Figure 3-19; grout was consolidated with a low force vibrator where additional grout was placed into the prisms after consolidation. To have a more uniform solidly grouted prism, reconsolidation and grout topping-off was necessary as the CMUs absorbed water from the grout. Excess grout was screeded off level with the top of the prism. Immediately following prism grouting, specimens were resealed in the moisture-tight bag. Prisms remained in the moisture-tight bags until 48 hours before their respective test age. Prisms stayed in their construction location for 48 hours. After 48 hours prisms were moved short distances to a lesser traveled area of the laboratory where floor space consumption and possible disturbance would be minimized. The prism construction location and storage location can be seen in Figure 3-20 (a) and (b).

Figure 3-17: Prism Construction

Figure 3-18: Removal of Mortar Fins and Droppings From Prisms

Figure 3-19: Grout Consolidation

(a) Construction Location

(b) Storage Location

Figure 3-20: Prism Locations

3.4 Specimen Testing

The compressive strength testing of the various specimens, CMUs, grouts, mortar, hollow prisms, and grouted prisms, are governed by their respective ASTM standard test methods. The testing procedures, apparatus, and limitations are described in this section. Photographs, sample identification, maximum applied force, maximum compression, testing time, and compression rate were recorded at the time of compression testing. All specimens were tested on a Baldwin-Tate-Emery Testing Machine, serial number 0401493 type UNIV, built by Baldwin-Lima-Hamilton Corp. in 1956; See Figure 3-21. This machine's load capacity is capped at 136.2 Mg (300 kips). The upper and lower platens are spherically seated; however, their size without modification is inadequate. A metal plate of sufficient thickness, according to the dimension requirements of ASTM C1314 Section 10.1 through 10.1.2 and Annex A1, was attached to the machine's upper platen by welding [12]; see Figure 3-22. The factory lower platen was significantly larger than that of the upper; however, it still required an additional metal plate. This plate could have smaller dimensions in comparison to the upper plate and it simply rested on the lower spherically seated platen.

ASTMs C1314, C1019, and C140 require that prism, grout, and CMU specimens be capped in accordance with ASTMs C1552 and C617 respectively. ASTM C109/109M, governing mortar cube compressive strength, specifies that the cube not be capped. All capping was completed with a high strength gypsum cement capping compound, Hydrocal White Gypsum Cement, which has the physical property of 34.5 MPa (5 ksi) strength.

Figure 3-21: Compression Testing Machine

Figure 3-22 : Welding of Testing Machine Upper Platen

The prisms and CMUs had loose protrusions of mortar and grout from construction. The protrusions were removed from the surface with an abrasive stone on the top and bottom bearing surfaces prior to capping [31]. The dried powered form of the gypsum cement was mixed with potable water in a mechanical mixer; see Figure 3-23. The rapidly curing gypsum and water cement mixture was spread onto a capping plate. The capping plate was a 6 mm (0.25 inch) thick glass 304.8 mm (12 inch) square with an oil coating for easy removal after drying [32]. A CMU block was placed on the top side of the glass capping plate creating an even pressure; the gypsum cement cap was, by observation, an average 3 mm (0.125 inch) in thickness [31]; see Figure 3-24. Capping was performed on a flat surface where capped specimens would not be disturbed until after they had dried [31]. If caps were deemed imperfect, they were removed and replaced with new ones [31]. No specimen receiving a cap was tested prior to at least 2 hours' worth of drying time [31]. Figure 3-25 shows a prism after receiving a gypsum cap. Prism specimens that appeared to have been disturbed or had significant grout shrinkage were discarded prior to capping. Disturbed specimens appeared to have CMUs that were misaligned or had gaps in between the mortar and CMU in one or more locations.

Grout compressive strength specimens were capped very similarly to prism and CMU specimens. It was not necessary to place a CMU block on the grout specimen to ensure it being plumb. Both bearing surfaces could be capped at the same time which helped to guarantee that no cap was off-centered.

Figure 3-23: Mixing of Gypsum Cement Cap

Figure 3-24: Capping of Prisms

Figure 3-25: Capped Prism

3.4.1 Concrete Masonry Unit Compressive Strength

At minimum, 3 concrete masonry units were tested for their compressive strength at age intervals 14, 28, 42, 56, and 90 days. CMU testing within the scope of this research is not necessary; however, including the strength of the CMUs at the same intervals as grout, mortar, and prism specimens can help to attribute strength gains or losses to the appropriate prism constituent as well as insure that specimens perform as expected according to similar studies of compressive strength of masonry prisms. The testing procedure for concrete masonry units used is detailed in ASTM C140 Section 7.4. The CMUs differ from the prism CMUs in their potential moisture content. The prisms were sealed in moisture-tight bags which they were removed from two days prior to compression testing where condensation was present on the interior of the bags. However, no CMUs had surface moisture present during compression testing [20]. Specimens were identified by their appearance, (single CMU), age in respect to prism, grout, and mortar samples, as well as specimen number. The area of the CMU specimens used in conjunction with the maximum recorded compressive force were presented previously in Table 3-2, expressed as the hollow/ungrouted bearing area, explained in Section 3.2.1 of this report.

3.4.2 Mortar Compressive Strength

The Standard Specification for Mortar for Unit Masonry indicates that compressive strength is to comply with Test Method C109/109M [26]. Mortar specimens were tested immediately upon removal from the moist room with their surfaces deprived of free moisture [27]. Bearing surfaces were plane and found to be parallel to each other. Specimen centroids were placed in line with the loading axis of the testing machine with platens that were free to tilt [27]. A strain rate was employed for consistency and ease of use with the testing computing software. The area used with the recorded loads to obtain units of pressure is displayed in Table 3-10. The measurements shown in this table are the result of measuring and averaging a group of 12 mortar cube specimen dimensions.

Table 3-10: Mortar Cube Dimensions

Average Dimension		Average Area	
mm	in	mm	in
51.20	2.02	2621.59	4.06

3.4.3 Grout Compressive Strength

Duel governance of the measuring of compressive strength of masonry grout is found in ASTMs C1019 and C39. Both test methods stress the importance of testing grout in a moist state [25, 33]. Test specimens were removed from the moist room, capped, and subsequently compression tested after the allotted two hour gypsum cap drying period. A continuous loading rate was applied through the duration of the test in a similar method as CMU, mortar, and prism specimens. Strain rate, rather than stress rate, controlled the loading force; for example, a majority of the specimens were loaded at 1.27 mm/min (0.05 in/min). Load was applied until a fracture pattern was visible and the load indicator had significantly decreased in value [33].

Area of the grout specimens, which were derived from extracting the filled cores of CMUs, was determined from averaging the area of 12 grout specimens. The perimeters of the specimen bearing surfaces were traced. Their outline was measured with a planimeter resulting in an area measurement. The area of the top of the grout specimen is slightly smaller than that of the bottom. The area of the top and the bottom was averaged to find one area for each specimen. A single area describing all of the grout specimens was determined by taking the mean of the 12 specimen sample which was found to be 14,064 mm^2 (21.8 in^2).

3.4.3.1 Method Conversion Factor

As mentioned in Section 3.3.2.2, it was necessary to establish a conversion factor between the standardized ASTM method of testing masonry grout and the method utilized in this testing program. The standard method described in ASTM C1019 of forming grout specimens was employed on a total of 12 samples and another 12 core-filled samples were created to establish the conversion factor between the two methods. A separate batch of grout, mimicking grout type 1, for this experimentation was manufactured (Table 3-11 for the grout mix used). A slump of 215.9 mm (8.5 inches) with the grout at 18.9°C (66°F) in a 20°C (68°F) ambient environment was recorded. The grout was mixed according to specifications in a 0.28 m^3 (10 ft^3) Essick mechanical mixer. Due to the later date at which the comparative groups were made, CMUs and fine and coarse aggregate in-situ moisture contents were again determined. Table 3-12 and Table 3-13 show the summary of the moisture testing. The aggregate absorption previously reported is held as the absorption values for these same aggregates.

Specimens receiving the standardized treatment were poured into a mold formed by four CMUs with a 100x100x9 mm (4x4x0.35 inch) non-absorbent acrylic block used as a spacer. A paper liner was used as a permeable barrier between the CMUs and the grout for easy removal of the molds; refer to Figure 3-26 for depiction. The grout specimens were cured with a moist towel covering the top for a period of 48 hours; after which they were removed from their mold. The specimens were saw-cut to form bearing surfaces that were 88.9 mm (3.5 inches) in length and width and with a height of 177.8 mm (7 inches), which was within the permissible 5% tolerance. Actual recorded dimensions are shown in Appendix A while dimensions used for bearing area and required height to width ratio are presented in Table 3-14.

Specimens in the conversion group utilizing the filling of CMU cores followed the method outlined in Section 3.3.2.2. All 24 specimens making up the conversion group were compression tested on the same day and on the same testing apparatus after following compression testing and capping methods explained in Section 3.4 and 3.4.3. Specimen results are available in Appendix A. Data was treated as will be described in Section 4.2. The conversion factor being used to relinquish differences between the two methods of grout testing is 1.11 times the recorded values.

Table 3-11: Conversion Group Grout Design

Constituent	Weight Contribution			Water Cement Ratio
	kg	lb	%	
Sand	80.8	178.1	50.2	0.843
Gravel	34.2	75.4	21.3	
Free Water	21.0	46.2	13.0	
Portland Cement	24.9	54.8	15.5	

Table 3-12: CMU Moisture Content for Grout Conversion Group

Sample #	Moisture Content %
1	0.801
2	0.809
3	0.685
4	0.692
5	0.810
6	0.687

Table 3-13: Aggregate Moisture Content for Grout Conversion Group

Aggregate Type	Moisture Content %
Fine	0.00119
Coarse	0.00067

Table 3-14: Conversion Group Dimensions

Average Width		Average Height		Average Height to Width Ratio	Average Area	
mm	in	mm	in		mm^2	in^2
88.47	3.48	176.04	6.93	1.99	613.14	24.14

Figure 3-26: ASTM Standardized Grout Specimen

3.4.4 Prism Compressive Strength

Just prior to the compressive strength test, prism specimens were measured in accordance with Section 8.2.1 of ASTM C1314. Of particular interest was prism height for strain measurements. Also measured, but not specified in the test method, was the thickness of the mortar joint. While the experienced masons constructing the prisms were instructed to assemble the prisms with a 10 mm (0.375 inch) mortar joint thickness, mason perception of this distance can vary. Mortar thickness can play a role in the compressive strength of the prism, especially in ungrouted prisms [15]. The average mortar thickness was determined to be 12.3 mm (0.48

inches). A summary of the average height and mortar thickness of individual specimens is given in Table A-6 and Table A-7 of Appendix A.

Prisms were seated in the testing machine on cleaned platens with centroidal axes in line with that of the machine's loading axis. The platens were checked to ensure their ability to pivot freely. While half of the expected load can be applied to the prism specimens at any rate, a continuous strain rate was applied from initial loading until failure. The latter half of the loading is specified to be completed at a uniform rate taking between 1 and 2 minutes [12]. Often, prisms which have failed under loading did not possess enough external physical characteristics to determine a mode of failure. Specimens that exhibited this behavior experienced an additional duration of loading until enough evidence of a mode of failure was present [12]. Compressive strength of each masonry set is to be reported to the nearest 69 kPa (10 psi) [12].

4 Results

4.1 Overview

Results of the compression testing performed on the CMUs, grouts, mortar, and prisms are presented in this chapter. Supporting documentation for the cause of the expected/ unexpected results and required ASTM reporting are included. Modification of the data, as was necessary, is discussed. Individual specimen results are located with additional supporting tables and figures in Appendix A and Appendix B which are pertinent to the overall results presented within the following sections. Stress/strain curves are presented in Appendix A.

4.2 Data Treatment

The bulk of the data and all compression testing were recorded by the Instron Merlin software which monitors the UNIV Baldwin testing machine, with time (sec), either a positive or negative extension (inches), and load (kips) being the essential measured quantities. Time is important as the specimens must break within 1 to 2 minutes after reaching half of the expected compressive strength. As aforementioned, the machine relies on a constant rate of strain. A rate of strain to match a 2 to 4 minute testing beginning with no load and ending with failure was used to attempt to adhere to time-to-failure restrictions and software limitations. The total extension is a function of the extension rate and the time until the maximum load is achieved.

Extension is used with original specimen height to calculate strain. Load is used in conjunction with the area of the specimen loading surfaces to obtain stress.

Modification to the recorded data becomes necessary when a number of initial conditions are present. The software program allows for resetting of the extension gage just prior to testing. As minute changes are recorded, often the first recorded measurement is either slightly less than zero or slightly more. The same situation can be applied to the load. The initial extension and load just prior to the beginning of the testing should both record zero. Initial extension and load recorded at the beginning of the test is subtracted out of all of the respective points. Depending on whether or not the gages were reset or what the initial readings indicate become irrelevant.

When the specimen is placed on the lower platen, the upper platen toggles are used to cover the relatively large distance between the upper platen and the top bearing surface of the specimen being tested. The upper platen is brought into contact with the top of the specimen, after which the lower platen toggle is used to move the entire specimen in full contact with both platens. This process is followed as the upper platen moves more rapidly and loading is not permitted to initiate from the upper platen toggles; due to the sensitivity of the device, the loading force is supplied by the hydraulics below the lower platen. Upon moving the platens into position the specimen can become slightly pre-loaded; this force is the load “zeroed” as prescribed above. More often than not, the initial location of the platens is not enough to accommodate for the specimen’s settlement into position. A large portion of the recorded extension can come from the settlement. Inaccuracies in strain are calculated as a result. The time recorded to cover this essentially moot compressional strength loading period can be extensive and hard to predict. Break times can seem drawn out; when in actuality the loading period is satisfactory.

To account for the strains and corresponding stress recorded during the settlement phase additional data modification is necessary. Figure 4-1 shows a typical stress strain curve without data modification. While not noticeable on this scale, the first recorded point is not at zero stress and zero strain. This was removed with the remedy described above. Notice the initial strain up to approximately 0.5%. This flat portion of the graph is deemed as specimen settlement; however not all of this may indeed be settlement and settlement data points could still be of importance. A standardized procedure was discretionarily chosen to account for settlement. It was first assumed that any stress less than 1% of the maximum stress went to settlement. When stresses were recorded less than this amount both the stress and corresponding strain were set aside. The set aside stresses and strains were averaged generating one new data point. This new data point is used as the starting point of the graph- in other words the new origin. To do so, the averaged stress result was removed from the remaining data points; the same was done for the strains. Figure 4-2 comparatively shows the stresses and strains with the data modified. While there still appears to be some settlement taking place, a larger settlement recording such as in this example is dramatically reduced. When less settlement was recorded initially, the graphical representation has little effect to the flattened beginning to the curve.

Figure 4-1 and Figure 4-2 also differ in that the modified data does not include all of the recorded data after the maximum recorded stress. For samples that required additional stresses and strains to induce a visible and easily recognizable failure mode many data points were recorded after failure. For presentation purposes, after the stress has decreased 50% of the maximum recorded, the graph is terminated.

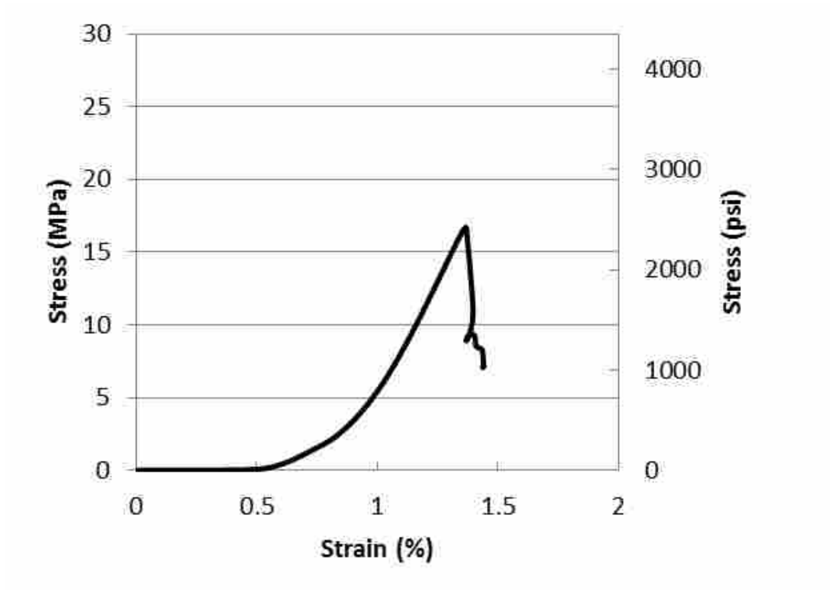


Figure 4-1: Example Unmodified Stress vs. Strain Curve

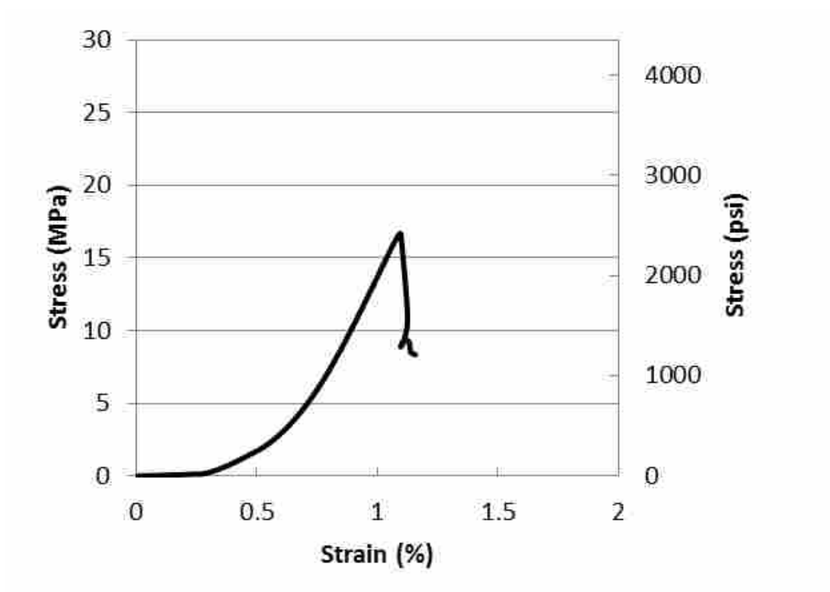


Figure 4-2: Example Modified Stress vs. Strain Curve

Data reduction is viable and applicable to the maximum recorded stresses. When specimen quantity is greater than three it is appropriate to determine if the recorded strengths are related to each other. Since a set is defined within the various ASTMs to be composed of three specimens reductions of certain specimen types is not feasible [12, 18]. Methods used for determining whether data is reducible can change the results and change the conclusions based upon those results. Compressive strength results from every test for each specimen type and age that has been recorded has been presented in Appendix A. All of the reported results are used in establishing the average compressive strengths rather than eliminate specimens for excessively high or excessive low strength in order to reduce bias stemming from a selection of a reduction method. At all times three or four specimens of each variation and age are used in the computation of the reported average compressive strength. After the average compressive strength is determined it is then rounded as instructed by ASTM C1314.

The data modification tactics detailed above alters the data slightly from that outputted by the computer software. The compressive strengths reported for the prisms are of that determined as a result of the modified data. The compressive strengths of the CMUs, mortar, and grout are of the unmodified data. The greatest advantage of data modification is to correct stress strain curves. Since graphical representations of the stress and strain during a specimen test is not essential to the CMUs, mortar, and grout, no modification on these specimen types has been performed. In order to justify comparisons between unmodified and modified data, Table 4-1 has been prepared. This table presents unmodified and modified compressive strengths of the CMUs. The percent change in the data is deemed small enough to make direct comparisons between reported unmodified and modified compressive strengths.

Table 4-1: Unmodified and Modified CMU Compressive Strength Summary Comparison

Test Period	Relative Age	Average Compressive Strength				Percent Change
		Modified		Unmodified		
#	days	MPa	psi	MPa	psi	%
1	14	25.30	3670	25.37	3680	0.27
2	28	23.30	3380	23.30	3380	0.00
3	42	26.20	3800	26.27	3810	0.26
4	56	26.54	3850	26.61	3860	0.26
5	90	27.65	4010	27.92	4050	1.00

4.3 Concrete Masonry Unit Compressive Strength

Compressive strength summaries for the concrete masonry units are given in Table 4-2 and Figure 4-3. Based on the results, the target strength of the CMUs is most likely 24.1 MPa (3500 psi). The ages of the CMUs are unknown. CMU specimens are represented by a relative age which coincides with the age of other types of specimens. Both the ages relative to the time after construction and the test period are provided to deter from identifying that the actual ages of the CMUs are the same as other specimen types; test period 1 with a 14 day relative age corresponds to the 14 day actual age of the mortar, grout, and prism specimens.

Table 4-2: CMU Compressive Strength Summary

Test Period	Relative Age	Average Compressive Strength	
#	days	MPa	psi
1	14	25.37	3680
2	28	23.30	3380
3	42	26.27	3810
4	56	26.61	3860
5	90	27.92	4050

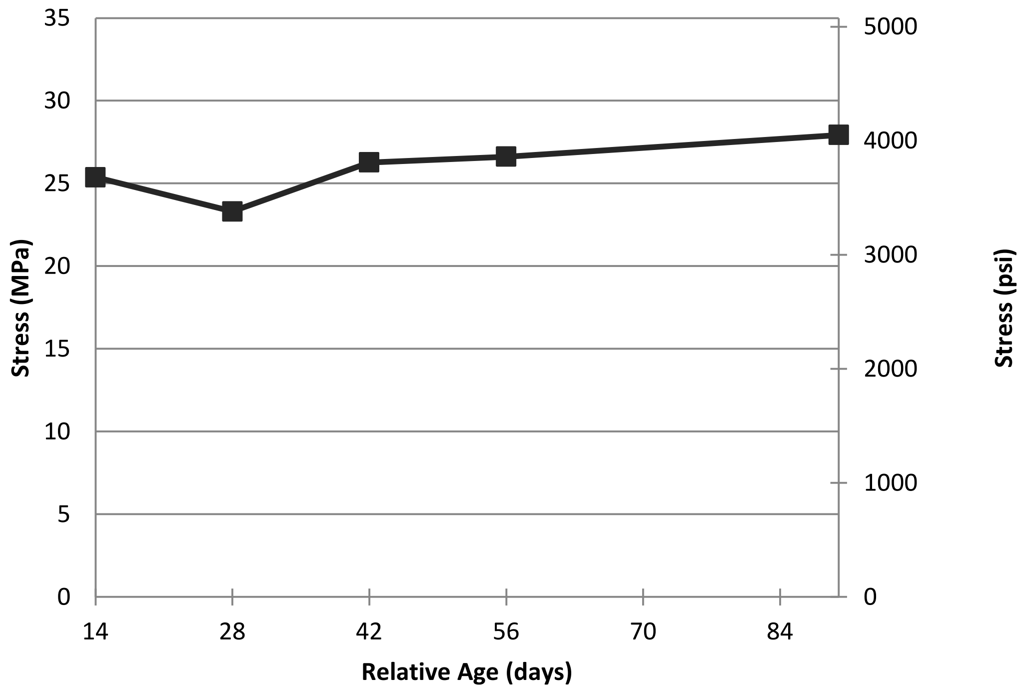


Figure 4-3: CMU Strength vs. Relative Age Summary

4.4 Grout Compressive Strength

Seven variations of grout were tested for the purpose of obtaining their maximum compressive stress capacity. The summaries of the strength of these grouts over time are summarized in Table 4-3 and presented graphically in Figure 4-4.

4.5 Mortar Compressive Strength

Summaries of the mortar compressive strength results are shown in Table 4-4 and Figure 4-5.

Table 4-3: Grout Compressive Strength Summary

Grout Type	Age	Average Compressive Strength	
#	days	MPa	psi
1	14	21.99	3190
	28	23.44	3400
	42	26.89	3900
	56	25.10	3640
	90	32.13	4660
2	14	9.03	1310
	28	14.34	2080
	42	17.65	2560
	56	22.96	3330
	90	28.41	4120
3	14	7.58	1100
	28	11.86	1720
	42	17.79	2580
	56	18.41	2670
	90	24.13	3500
4	14	4.00	580
	28	6.41	930
	42	11.03	1600
	56	12.41	1800
	90	17.24	2500
5	14	18.34	2660
	28	17.72	2570
	42	31.58	4580
	56	31.30	4540
	90	35.03	5080
6	14	18.68	2710
	28	17.65	2560
	42	23.65	3430
	56	26.34	3820
	90	30.61	4440
7	14	10.07	1460
	28	11.86	1720
	42	14.89	2160
	56	16.75	2430
	90	18.34	2660

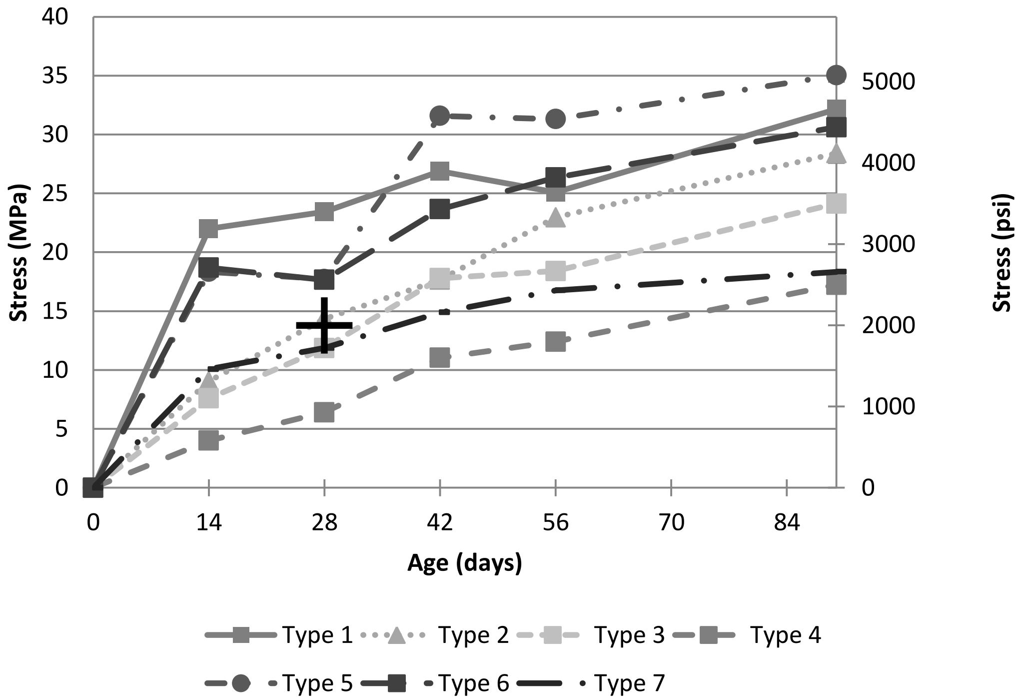


Figure 4-4: Grout Strength vs. Age Summary

Table 4-4: Mortar Compressive Strength Summary

Relative Age	Average Compressive Strength	
days	MPa	psi
14	18.00	2610
28	19.10	2770
42	23.58	3420
56	18.41	2670
90	21.72	3150

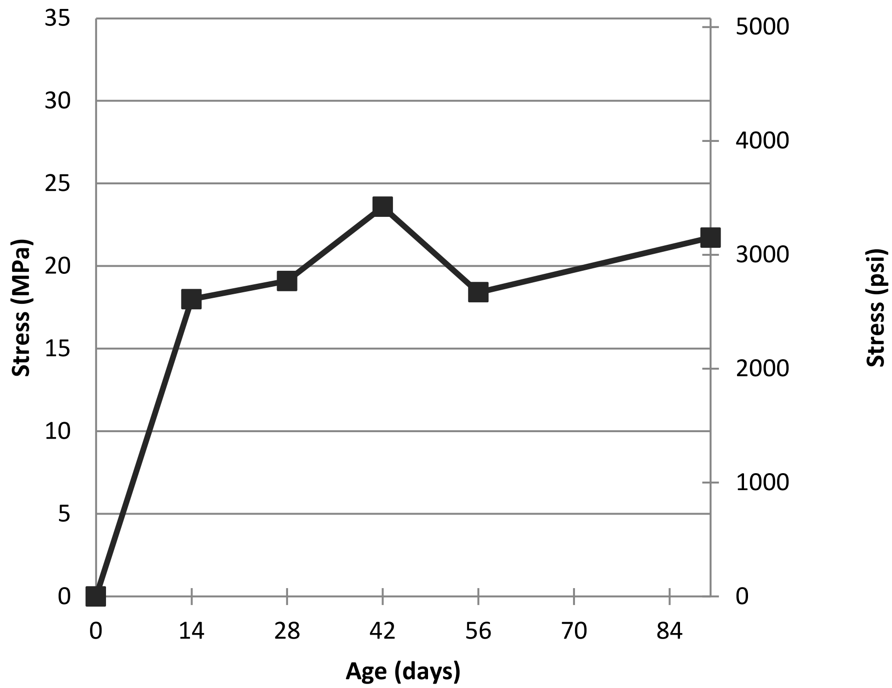
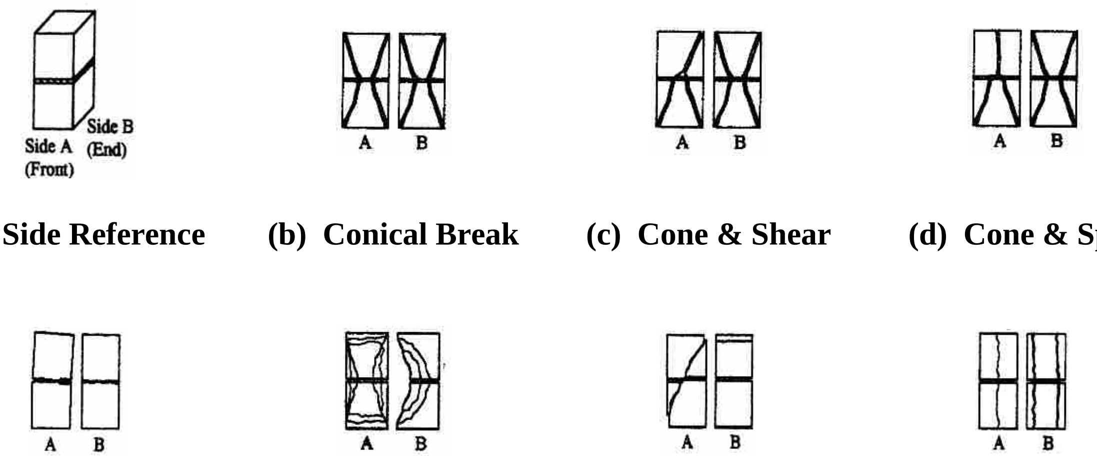


Figure 4-5: Mortar Strength vs. Age Summary

4.6 Prism Compressive Strength

Per ASTM C1314, the mode of failure should be described and illustrated [12]. Figure 4-6 shows the failure mode descriptions with a classification and visual representation while Table 4-5 shows the shorthand numerical designations for failure mode classifications used in this thesis. Appendix B contains photographs of failed prisms specimens for verification of the prism failure mode designations assigned in Table 4-6. While the prisms were loaded until a failure mode was present it was often difficult to assess which mode of failure was the mode that had occurred. In Table 4-6 there are cells that contain two failure mode identification numbers. The dual numbers indicate that it is probable that either of the two failure modes are the actual failure mode but either small fracture patterns or a failure which obliterated evidence made assigning a single mode of failure divisive.

The summaries of the compressive strength of the eight prism variations are shown in Figure 4-7 and summarized in Table 4-7.



(a) Side Reference **(b) Conical Break** **(c) Cone & Shear** **(d) Cone & Split**

(e) Tension Break **(f) Semi-Conical Break** **(g) Shear Break** **(h) Face Shell Separation**

Figure 4-6: Failure Mode Representations [12]

Table 4-5: Failure Mode Designations

Failure Mode	Number Designation
Conical Break	1
Cone & Shear	2
Cone & Split	3
Tension Break	4
Semi-Conical Break	5
Shear Break	6
Face Shell Separation	7
Not Available	8

Table 4-6: Prism Failure Mode Evaluation

Age days	Specimen #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #	Grout Type	Failure Mode #
14	1	0	2	1	7	2	1	3	3	4	8	5	8	6	4	7	2
	2		5		5		3		2		3		3		5		3
	3		2		3		2		3		2		5		4		2
28	1		3		2		1		3		1		6		3		3
	2		3		3		1		2		1		6		3		2
	3		3		3		1		2		3		5		2		3
	4		3		1		1		2		1		3		3		2
42	1		3		5		3		3		3		2		5		2
	2		4,5		1		2		2		1		5		5		3
	3		3		3		5		2		5		5		2		5
	4		5		5		5		3		2		5		5		5
56	1		2		3		1		2		2		1		5		2
	2		5		1		5		3		2		3		5		2
	3		4,2		1		2		5		5		1		2		1
	4		4,5		1		3		3		3		2		5,6		1
90	1		6		2		2		5		5		2,5		5,6		3,6
	2		3		2		5		2		6		1		5,6		2,5
	3		3		2		5,6		2		6		1,5		2,6		2,5
	4		3,6		5		5,6		6		3		1,6		3		1

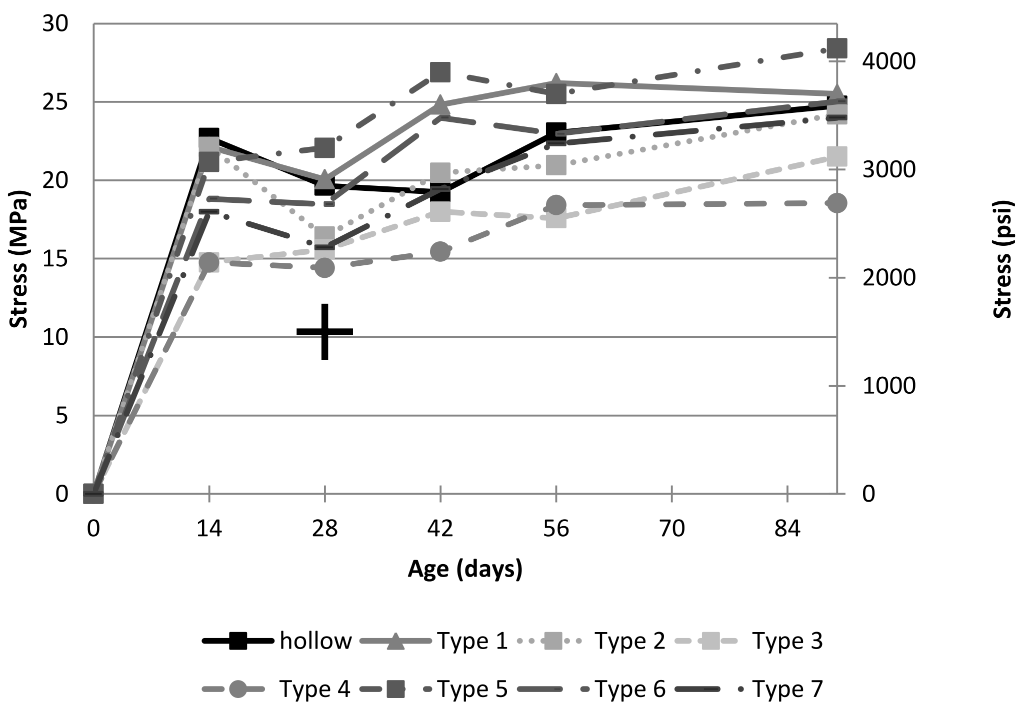


Figure 4-7: Prism Strength vs. Age Summary

Table 4-7: Prism Compressive Strength Summary

Grout Type	Age	Average Compressive Strength	
	days	MPa	psi
hollow	14	22.68	3290
	28	19.65	2850
	42	19.24	2790
	56	23.03	3340
	90	24.75	3590
1	14	22.13	3210
	28	20.06	2910
	42	24.82	3600
	56	26.20	3800
	90	25.51	3700
2	14	22.13	3210
	28	16.41	2380
	42	20.48	2970
	56	20.96	3040
	90	24.20	3510
3	14	14.75	2140
	28	15.58	2260
	42	18.00	2610
	56	17.58	2550
	90	21.51	3120
4	14	14.75	2140
	28	14.41	2090
	42	15.44	2240
	56	18.41	2670
	90	18.55	2690
5	14	21.17	3070
	28	22.06	3200
	42	26.89	3900
	56	25.51	3700
	90	28.41	4120
6	14	18.82	2730
	28	18.48	2680
	42	23.99	3480
	56	22.96	3330
	90	25.03	3630
7	14	18.00	2610
	28	15.72	2280
	42	19.44	2820
	56	22.34	3240
	90	23.99	3480

4.7 Result Comparisons

In the *Building Code Requirements and Specification for Masonry Structures* the requirements for the specified compressive strengths of both grout and masonry are detailed. Since only the code commentary mentions curing ages for strength development, it is inferred that the 28-day compressive strength 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 (1,500 psi) but be no greater than 27.6 MPa (4,000 psi) and f'_g to exceed or be equal to that of f'_m [11]. The ASTM Standard for grout stipulates its minimum strength at 14 MPa (2000 psi) at 28 days [18]. Table 4-8 summarizes the compliancy of the grouts and prisms to the ASTM Standards. In this table, an ASTM compliant grout reaches 14 MPa (2000 psi) by 28 days. Since no prism through 28 days achieved strength of 27.6 MPa (4,000 psi), a compliant prism has at least a compressive strength of 10.3 MPa (1,500 psi) by 28 days.

Building code compliance is determined using the specified compressive strength of components. The prisms and grouts tested for this research had no specified compressive strengths. The research intended on finding the compressive strengths with a grout, likely specified at 27.6 MPa (4000 psi), altered by changing the cementitious material composition. The strength, as a result, changed and each grout type no longer had a specified compressive strength. The prisms also had no specified strength. With grout type 1, the 24.1 MPa (3500 psi) CMU, and the 17.2 MPa (2500 psi) mortar, system strength would indicate that the specified compressive strength of this specific arrangement would likely be 20.7 MPa (3000 psi); the prism results agree. The grout would have a greater specified compressive strength (27.6 MPa) than the specified compressive strength of the prism (20.7 MPa) and compliancy could easily be validated with testing of the grout and prism. For the remaining six types of grout and prisms code system compliancy assertion is impossible because components have no specified compressive strength. In order to make compliancy system assertions in this regard the actual compressive strengths of the grouts and prisms would have to be considered the specified compressive strengths.

Table 4-8: Strength of Grouts and Prisms Compliancy

Grout Type	Grout ASTM Compliancy	Prism ASTM and Building Code Compliancy	Grout Building Code Compliancy
hollow	NA	COMPLIANT	NA
1	COMPLIANT	COMPLIANT	COMPLIANT
2	COMPLIANT	COMPLIANT	NA
3	NON-COMPLIANT	COMPLIANT	NA
4	NON-COMPLIANT	COMPLIANT	NA
5	COMPLIANT	COMPLIANT	NA
6	COMPLIANT	COMPLIANT	NA
7	NON-COMPLIANT	COMPLIANT	NA

4.8 Data Inconsistencies

Inconsistencies are observed in the compression results of various specimens. Perhaps the most obvious and regular form of discrepancy is strength loss. Strengths of specimens at 14 days should be the lowest recorded value of compressional strength as strength gain occurs as concrete cures. In addition, prisms with grout that contain fly ash and slag should cure more slowly and higher strengths should be observed with larger strength gains between testing ages. The results from this study show dips in strength at the 28-day age. While this is of concern, it does not affect any conclusions that can be drawn about whether or not prisms attained compressional strength minimums due to the fact that even the lowest recorded strength of a prism is well in excess of the minimum required. Most concern is with grout specimens that dip in strength at the 28-day age testing period. The strengths of the grouts are significantly weaker than that of the prisms, as expected. Every bit of strength gain is relevant to the conclusions. This research intends on extending the addition rates of supplementary cementitious materials or the time at which strength must develop. With strength reduction at 28 days and 28 days being a prominent test age for grout, some reliability apprehensions in the accuracy of the results ensues. Either 14-day tests results are "too high" or 28-day test results are "too low". Attempting to distinguish which result is most probable is inconclusive. When comparing the grout strength to that of the prism strength for assessing compliancy to the building code as discussed in Section 4.8, the dips in strength for both the grouts and prisms make this assessment much more difficult. Refer to Table 4-9 for an example of when the grout loses strength between the 14 and 42-day tests. This grout would be determined to be non-compliant to the specified compressive strength of grout building code requirements. Since the prism is developing strength much slower than that of the grout and by observing the strengths at the 14 and 42-day ages it can be asserted that if it were not for the strength loss inconsistency this grout would be code compliant.

Table 4-9: Example of Grout and Prism Strength Dip Comparison

Grout Type	Age	Prism Average Compressive Strength		Grout Average Compressive Strength	
	days	MPa	psi	MPa	psi
5	14	21.17	3070	18.34	2660
	28	22.06	3200	17.72	2570
	42	26.89	3900	31.58	4580
	56	25.51	3700	31.30	4540
	90	28.41	4120	35.03	5080

Since there was difficulty in assessing an appropriate strain rate at which to set the loading apparatus, specimens underwent changes in this rate apparent to trial breaks and was further refined as testing progressed. Consistency and the effect of the rate was discovered during experimentation and not prior. Some test specimens required greater strains in order to eliminate any settlement and subsequently time for loading making a 1 to 2 minute second half of loading difficult to predict. When specimens undergo increased strain rates or receive loading quicker than anticipated, strengths should be elevated as indicated by Maurenbrecher's testing procedures research and confirmed through a series of laboratory variable rate testing on CMUs [17]. Further, slower rates should induce lower compressive strengths. Even with these accepted notions of loading rates, specimens did not necessarily perform in these manners. A few specimens achieved higher, in relation to others of its kind, strength recordings while being tested for longer than average durations.

Discrepancy with ultimate strength can further be attributed to machinery limitations and specimen fabrication methods when considering end bearing affects at the platens. The lateral confinement at the tops and bottoms of the prisms increases the apparent compressive strength and changes the mode of failure to a shear mode which is not observed for walls or for prisms composed of more courses [15]. A shear failure mode was quite common. While prism specimens do meet minimum height to width ratios for testing, perhaps adhering to the minimum number of courses rather than the maximum is not as representative of real construction. It is important to note, however, that all specimens in testing undergo platen confinement and comparisons between them become more reasonable. Grout specimens require at least a 2:1 height to width ratio. Core filled and extracted specimens were slightly below this requirement. Even with a satisfactory conversion comparison group, induced failure modes are quite different than of those projected and, based on observation, different than the failure of the grout within the prisms. Effects of removing the grout specimens from their CMU core molds are also unknown and it is unclear whether the conversion comparison group eliminated these effects.

Fluctuation in the strength gain figures can be further attributed to researchers. Specimens were tested by a small group of students while methods remained similar, fatigue or imprecision with specimens can result in inaccurate assessments of strength. For instance, misalignment of a specimen's axes with that of the loading device, assuring platen maneuverability, or disturbance of a specimen, can all result in strength recording variations. The prisms were also handled to a greater extent than any of the other specimens. Prisms weighed close to 36.3 kg (80 lb) and relocating and rotating were necessary for capping; incidental or unnoticed disturbances and induced moments on the assembly can break the chemical and physical bond between the mortar and the CMUs.

The mortar of the prisms exists to provide uniform bearing and bond individual units into a composite assemblage [2]. The thicknesses of the mortar were, measuring at mid-length of each prism specimen, not uniform and the average mortar thickness was greater than the required 10 mm (0.375 in) thickness. A thicker mortar bed can correspond to a lower compressive strength [15]. The mortar thickness would be of greater concern had the prisms not attained minimum compressive strength or were not fully grouted. Lower strengths can be attributed to the thickness of the mortar but it does not impact the conclusions of this thesis.

5 Conclusions

5.1 Summary

A prism testing scheme was devised to determine if the addition rates of supplemental cementitious materials to masonry grout could be increased to promote the economic and environmental benefits and feasibility of masonry construction. Grouts with higher than currently allowed addition rates had previously been tested by the CMACN. Grouts that do not meet the ASTM strength at a 28-day curing age or the proportioning requirements could be used in solidly grouted prisms to see if the assemblage could meet masonry strength minimums.

Constituents of the masonry prisms were tested for the purpose of comparing their strength gain over time to that of the masonry prisms. Simultaneous research conducted with mortar types N and S identical to this report's scope as well as more expansive research on the seven variations of the grouts can be referenced. Previous CMACN research and adherence to their material selection and ability to gather necessary materials narrowed the scope of this prism testing scheme. This report focused on the compressive strength of masonry prisms. Prism compressive strength testing should mimic the construction scenarios. While the materials selected as representative of those used in California, Nevada, and Utah and methods of testing are consistent with the various codes and standard practices, prism failure modes under axial compression resembling that of failure found in concrete masonry walls are more accurately modeled with a larger height-to-thickness ratio than of that used in this testing scheme.

CMUs, type M mortars, grouts, and prisms were tested for strength against compressional loading. Prism recorded data was modified to eliminate the effects of specimen settlement and irrelevant pre-loading stresses and strains; some discretionary practices are used. All CMU, mortar, grout, and prism specimen recordings were used in computations of average compressive strengths to portray the most credible data and eliminate outliers while not advancing any preconceived agenda. Averaged values of compressive strength are reported. Grout specimen results are modified by a conversion factor determined by testing and comparing the ASTM standard method for testing masonry grout and the core-filled and extraction method employed in this testing scheme. Prisms are further evaluated by reporting a failure mode. Inconsistencies and discrepancies with the results are discussed at length.

5.2 Findings

The strength of the block is attributed to most of the strength of the prisms and should the prisms had not made strength a remedy of increasing the block strength could be employed. Had the minimum compressive strength CMU been chosen the results could have changed significantly. Mortar strength progresses to well over 10.3 MPa (1500 psi) within 14 days, which is all it must attribute to the prism strength to meet f'_m. However, mortar in the prism is stronger than the cubed mortar specimens because water is absorbed by the units which reduces the water-cement ratio. The mortar strength has effect on the prism compressive strength but at all times the mortar itself is not the factor that is the most hindering to the overall compressive strength in this experimentation.

Grout types 1, 5, and 6 achieved the minimum 13.8 MPa (2000 psi) strength at 14 days and these grouts along with type 2 meet 28-day strength requirement. All grouts eventually achieve this strength; however types 3 and 7 do this at 42 days. The types that do not meet strength at early ages also impede on the compressive strength of the prisms. When the grout compliancy depends on both the ASTM Standards and that of the building code, with the specified compressive strength assumptions asserted in Section 4.7, the only code compliant grout is type 1. Prisms with grout types 3, 4, and 7 have the lowest compressive strengths. Prisms with type 7 grout eventually gain equitable strength in comparison to hollow prisms at the latest age.

Even with data inconsistencies as discussed in Section 4.8 of this report, all prisms, using a mean strength, attained the minimum specified compressive strength of masonry. This strength was also achieved at 14 days after specimen construction, leading one to conclude that weaker grouts could be used and minimum strengths can still be reached. Since a majority of the prisms were not using grouts up to code standards it is evident that the strength of the grout has small influence on the compressive strength of the masonry. Since the masonry code intertwines the compressive strength of masonry with other aspects not related to compressive strength of masonry a solid, and singular conclusion about whether addition rates of supplementary cementitious materials to masonry grout can be increased based solely on this testing scheme is impossible. Understanding that the assumptions of the masonry code in using f'_m rather than f'_g limit the strength of the grout to that of the masonry and thus limit the physical make-up of the grout.

Relying on both grout and prism data the primary deduction that evolves is that there should be more distinctive and further unrelated ASTM standards for masonry grout and concrete. Grout compressive strength testing determined by this research and by that of Twinning Laboratories conclusively indicates that larger addition rates of both fly ash and fly ash-slag to masonry grout is plausible and falls within the bounds of 28-day strength requirements. Portland cement in concrete masonry grout can be replaced with 45 % class F fly ash. Portland cement in concrete masonry grout can be replaced with 25% class F fly ash and 50 % ground granulated blast furnace slag for a total replacement of 75%. Stretching of the allotted strength development time to 42 days can further increase these addition rates promoting extensive use of up to 55% replacement of Portland cement with fly ash and up to 85% of Portland cement with a fly ash-slag combination. When strength development relies primarily on compressive strength alone or when time can be allocated to further strength development for the purpose of using higher addition rates to benefit both project costs and environmental efforts these increased addition rates can be used, advancing this tool in sustainable design for engineers.

With the current masonry and ASTM specifications, the use of the supplementary cementitious materials of fly ash and slag should be more abundantly employed in masonry structures. The strengths of the prisms in this experiment with code compliant grouts using the recycled materials are comparable to that of the control group with an all Portland cement based grout. The current justification of not employing grouts with supplemental cementitious materials is the reliance on the unit strength method. Straying from the unit strength method, the cost savings from reduce Portland cement contents can be even more dramatic with higher addition rates in the code as advocated above. The costs referred to are monetary and not in terms of resources, as the use of the supplemental cementitious materials fly ash and slag have environmental benefits as well. Straying from the unit strength method and using the prism test method will encourage grout designs that incorporate recycled materials producing masonry structures that are more environmentally responsible and cost conscious.

5.3 Recommendations for Further Research

The *Building Code Requirements and Specification for Masonry Structures* employs the specified compressive strength of masonry throughout. It is important that the results reported here are conservatively represented in the equations that employ f'_m. Modulus of elasticity, nominal axial, shear, and combined strength of anchor bolts, axial, shear, and bearing strength, development length of reinforcing bars, unreinforced masonry, allowable forces, deflection, flexure, and shear equations all involve and rely on f'_m. Since the code stipulates that the specified compressive strength of grout, f'_g, be at least that of f'_m further tests assuring that lower actual compressive strengths of grout, do not disrupt the intensions of reliable design with masonry code equations are necessary. Prisms that approach the lower boundary strength would help to ensure that the grouts are stronger than the prisms and aid in code compliancy. This could be achieved by experimenting with lower strength CMUs.

Intentionally the water content was held constant and only adjusted to ensure that grouts would meet slumping requirements. This deliberate addition of water made for direct comparisons of all grout types. With the addition of the supplemental cementitious materials the slumps increased due to particle size and shape. Future testing could limit the slumps of each grout variation to 200 mm (8 in) which would decrease the water cement ratio and increase strength while not inhibiting workability. It could then be proved that by specifying and controlling slump that addition rates of supplemental cementitious materials could be increased further.

Methods of mixing the grout batches can also be researchable to determine if the aggregates and fine particles of the cementitious materials are evenly distributed. If during the mixing, water segregated or prevented a homogenous batch the potential for hydration and cementing is limited which would reduce compressive strengths. This research limited the quantities of fly ash in the fly ash-slag combination to 25% of the replacement cementitious material. Fly ash-slag combinations in concrete have established guidelines for their respective addition rates. However, high replacement proportioning and mixing must further be understood and re-explored in order to establish new replacement guidelines specified to masonry grout.

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Appendix A. Supplement Test Data

Table A-1: CMU Dimension Measurements for Standardization

(a) Metric Units

Specimen	Groove Dimensions		Height (H) at Mid-Length/Mid-Width				Length (L) /Width (W) at Mid-Height (in)				Web (t_w) Thickness (in)		Face Shell (t_{fs}) Thickness	
	Length	Width	Face 1	Face 2	Face 3	Face 4	Face 1	Face 2	Face 3	Face 4	Face 1	Face 2	Face 1	Face 2
#	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	19.4	19.4	192.9	192.1	193.7	193.7	194.5	193.7	194.5	194.5	33.5	32.9	45.7	45.3
2	18.7	19.2	193.7	193.7	194.5	193.7	195.3	194.5	195.3	192.9	33.5	32.5	45.7	45.3
3	18.5	19.8	193.7	193.7	194.5	193.7	195.3	195.3	195.3	193.7	33.7	32.5	45.9	46.4
4	18.8	19.7	193.7	192.9	192.9	192.9	195.3	194.5	193.7	193.7	33.1	33.4	45.2	47.0
5	17.8	19.8	193.7	193.7	193.7	192.9	194.5	194.5	195.3	194.5	33.5	33.4	45.3	46.4
6	18.2	19.5	193.7	192.9	193.7	192.9	195.3	194.5	195.3	193.7	35.2	35.1	48.7	47.1
Averages	19.1		193.4				194.5				33.5		46.2	

(b) English Units

Specimen	Groove Dimensions		Height (H) at Mid-Length/Mid-Width				Length (L) /Width (W) at Mid-Height (in)				Web (t_w) Thickness (in)		Face Shell (t_{fs}) Thickness	
	Length	Width	Face 1	Face 2	Face 3	Face 4	Face 1	Face 2	Face 3	Face 4	Face 1	Face 2	Face 1	Face 2
#	in	in	in	in	in	in	in	in	in	in	in	in	in	in
1	0.8	0.8	7.6	7.6	7.6	7.6	7.7	7.6	7.7	7.7	1.3	1.3	1.8	1.8
2	0.7	0.8	7.6	7.6	7.7	7.6	7.7	7.7	7.7	7.6	1.3	1.3	1.8	1.8
3	0.7	0.8	7.6	7.6	7.7	7.6	7.7	7.7	7.7	7.6	1.3	1.3	1.8	1.8
4	0.7	0.8	7.6	7.6	7.6	7.6	7.7	7.7	7.6	7.6	1.3	1.3	1.8	1.8
5	0.7	0.8	7.6	7.6	7.6	7.6	7.7	7.7	7.7	7.7	1.3	1.3	1.8	1.8
6	0.7	0.8	7.6	7.6	7.6	7.6	7.7	7.7	7.7	7.6	1.4	1.4	1.9	1.9
Averages	0.8		7.6				7.7				1.3		1.8	

Table A-2: Twining Laboratories Grout Specimen Compressional Strength Data Summary (English Units)

Age	100% Portland Cement	20% FA Replacement	30% FA Replacement	40% FA Replacement	50% FA Replacement	60% FA Replacement	50% FA & GGBFS Replacement	60% FA & GGBFS Replacement	70% FA & GGBFS Replacement	80% FA & GGBFS Replacement
days	psi	psi	psi	psi	psi	psi	psi	psi	psi	psi
7	2982.5	2780.0	2450.0	1540.0	1610.0	910.0	1890.0	2260.0	1940.0	1460.0
14	3285.0	2920.0	2970.0	2140.0	2090.0	1150.0	2890.0	3270.0	2770.0	1940.0
28	4062.5	3310.0	3830.0	2690.0	2880.0	1440.0	3310.0	3230.0	3410.0	2430.0
42	4175.0	3800.0	3880.0	3050.0	3130.0	1930.0	3660.0	4540.0	4210.0	2710.0
56	4300.0	4250.0	4650.0	3330.0	2960.0	2070.0	5010.0	4830.0	4260.0	3140.0
180	4120.0	5180.0	5670.0	4690.0	4330.0	3790.0	6210.0	6010.0	5260.0	3590.0

Table A-3: Determination of CMU Absorption, Density, and Moisture Content

Specimen	W_r, Received Weight	W_i, Immersed Weight	W_s, Saturated Weight	W_d, Dry Weight		Absorption		Absorption	Moisture Absorbed	Density		Moisture Content
#	lb	lb	lb	lb	kg	pcf	g/cm^3	%	%	pcf	g/cm^3	%
1	22.15	12.40	22.82	21.48	9.75	8.0	0.13	6.2	50.17	128.63	2.06	3.12
2	22.04	12.21	22.62	21.15	9.59	8.8	0.14	6.9	60.81	126.87	2.03	4.21
3	22.05	12.37	22.63	21.14	9.59	9.1	0.15	7.1	61.39	128.61	2.06	4.34
4	22.28	12.66	22.86	21.58	9.79	7.8	0.12	5.9	54.46	132.08	2.11	3.21
5	22.00	12.14	22.60	21.18	9.61	8.4	0.13	6.7	58.14	126.45	2.02	3.88
6	21.87	12.10	22.48	21.06	9.6	8.5	0.1	6.7	56.96	126.64	2.0	3.83
			Averages	21.27	9.6	8.4	0.1	6.6	56.99	128.21	2.1	3.76

Table A-4: Mortar Flow Data

Mortar Type	Measurement	Diameter After 25 Drops	Original Inside Diameter	Average Diameter Increase	Flow
	#	mm	mm	mm	%
M	1	111.7	101.6	10.2	10.04
	2	112.1			
	3	111.7			
	4	111.7			
	Average:	111.8			

Table A-5: Grout Control Group Result Summary

Casting Method	Specimen	Compressive Strength	Average Modified Compressive Strength		Standard Deviation		Coefficient of Variation	Method Conversion Factor
	#	psi	MPa	psi	MPa	psi	%	
Standard	1	4387.1	25.81	3743.5	8.04	1166.2	31.2	1.11
	2	4252.7						
	3	4520.6						
	4	3156.7						
	5	4153.9						
	6	4100.6						
	7	4315.2						
	8	4103.4						
	9	4417.4						
	10	4740.5						
	11	1513.0						
	12	1260.8						
Core-Filled	1	3665.0	23.22	3367.9	3.42	495.4	14.7	
	2	3817.2						
	3	1881.5						
	4	3296.8						
	5	3270.9						
	6	3481.6						
	7	3549.1						
	8	3674.3						
	9	3549.9						
	10	3353.5						
	11	3395.4						
	12	3479.7						

Table A-6: Average Prism Specimen Height and Mortar Thickness (Metric Units)

Age	days	14		28		42		56		90	
Grout Type	Specimen #	Average Height mm	Average Mortar Thickness mm	Average Height mm	Average Mortar Thickness mm	Average Height mm	Average Mortar Thickness mm	Average Height mm	Average Mortar Thickness mm	Average Height mm	Average Mortar Thickness mm
hollow	1	401.24	12.30	400.84	13.10	396.08	13.10	402.83	10.72	399.26	11.91
	2	399.65	12.30	402.83	12.70	399.26	11.91	400.45	11.91	402.43	11.51
	3	400.45	13.10	400.05	11.91	401.24	13.89	400.84	12.70	400.05	11.11
	4	-	-	400.45	13.49	400.84	9.92	399.65	13.49	400.05	12.30
1	1	404.81	13.10	403.62	13.89	403.23	15.88	402.43	11.51	396.48	12.70
	2	404.81	13.89	403.62	13.89	400.84	13.49	403.62	11.51	398.46	11.91
	3	403.62	11.11	404.81	15.08	398.86	12.70	401.24	11.51	400.05	11.91
	4	-	-	403.62	12.70	400.84	11.91	402.03	11.51	400.84	11.11
2	1	400.05	12.70	398.86	11.30	398.46	9.53	399.65	9.92	400.84	12.30
	2	399.26	10.32	404.42	13.49	397.67	13.49	400.84	11.11	399.65	11.91
	3	404.02	10.72	400.84	12.70	400.05	12.70	401.36	10.32	398.07	12.30
	4	-	-	406.00	11.91	400.05	13.49	400.05	10.72	402.03	12.30
3	1	406.00	14.68	400.84	11.11	398.46	12.30	403.23	11.91	404.02	13.89
	2	406.40	14.29	411.56	13.10	403.62	12.70	399.26	9.92	398.86	11.51
	3	404.02	13.49	406.80	16.67	396.88	12.70	400.05	11.91	401.64	12.70
	4	-	-	403.62	14.68	400.84	12.70	400.05	11.51	398.07	13.89
4	1	381.79	9.53	401.64	13.89	392.91	14.29	401.24	10.32	404.02	11.11
	2	403.23	13.10	403.62	13.10	398.46	13.49	402.83	12.30	403.23	11.91
	3	404.81	12.30	403.62	15.08	397.27	11.91	399.65	12.30	400.84	12.70
	4	-	-	403.62	13.89	400.05	11.91	399.65	9.53	402.03	11.51
5	1	405.21	15.08	400.84	12.70	400.84	11.91	401.64	12.30	400.05	8.73
	2	406.40	13.49	402.03	12.70	398.46	11.91	401.64	12.70	402.83	9.92
	3	406.00	14.29	398.86	12.70	400.05	12.70	399.26	12.30	403.23	10.72
	4	-	-	403.62	12.30	401.24	13.10	402.83	12.30	402.43	13.10
6	1	403.62	13.10	400.45	12.70	400.84	10.32	402.43	11.51	401.64	10.72
	2	402.03	9.53	403.23	13.10	402.43	11.91	402.43	12.30	401.24	10.32
	3	405.21	10.72	400.84	11.11	402.83	11.11	400.45	10.32	401.24	11.11
	4	-	-	404.02	12.30	399.26	11.91	397.67	9.92	401.24	10.72
7	1	402.83	12.70	403.23	13.89	399.26	11.11	403.62	11.11	406.40	13.49
	2	403.23	12.70	401.24	11.51	402.43	12.70	400.05	11.11	403.23	13.89
	3	402.83	11.91	402.82	19.84	401.11	12.70	402.43	12.30	400.45	11.91
	4	-	-	404.02	11.91	401.64	11.11	402.43	12.70	401.64	13.10

Table A-7: Average Prism Specimen Height and Mortar Thickness (English Units)

Age	days	14		28		42		56		90	
Grout Type	Specimen #	Average Height in	Average Mortar Thickness in	Average Height in	Average Mortar Thickness in	Average Height in	Average Mortar Thickness in	Average Height in	Average Mortar Thickness in	Average Height in	Average Mortar Thickness in
hollow	1	15.80	0.48	15.78	0.52	15.59	0.52	15.86	0.42	15.72	0.47
	2	15.73	0.48	15.86	0.50	15.72	0.47	15.77	0.47	15.84	0.45
	3	15.77	0.52	15.75	0.47	15.80	0.55	15.78	0.50	15.75	0.44
	4	-	-	15.77	0.53	15.78	0.39	15.73	0.53	15.75	0.48
1	1	15.94	0.52	15.89	0.55	15.88	0.63	15.84	0.45	15.61	0.50
	2	15.94	0.55	15.89	0.55	15.78	0.53	15.89	0.45	15.69	0.47
	3	15.89	0.44	15.94	0.59	15.70	0.50	15.80	0.45	15.75	0.47
	4	-	-	15.89	0.50	15.78	0.47	15.83	0.45	15.78	0.44
2	1	15.75	0.50	15.70	0.45	15.69	0.38	15.73	0.39	15.78	0.48
	2	15.72	0.41	15.92	0.53	15.66	0.53	15.78	0.44	15.73	0.47
	3	15.91	0.42	15.78	0.50	15.75	0.50	15.80	0.41	15.67	0.48
	4	-	-	15.98	0.47	15.75	0.53	15.75	0.42	15.83	0.48
3	1	15.98	0.58	15.78	0.44	15.69	0.48	15.88	0.47	15.91	0.55
	2	16.00	0.56	16.20	0.52	15.89	0.50	15.72	0.39	15.70	0.45
	3	15.91	0.53	16.02	0.66	15.63	0.50	15.75	0.47	15.81	0.50
	4	-	-	15.89	0.58	15.78	0.50	15.75	0.45	15.67	0.55
4	1	15.03	0.38	15.81	0.55	15.47	0.56	15.80	0.41	15.91	0.44
	2	15.88	0.52	15.89	0.52	15.69	0.53	15.86	0.48	15.88	0.47
	3	15.94	0.48	15.89	0.59	15.64	0.47	15.73	0.48	15.78	0.50
	4	-	-	15.89	0.55	15.75	0.47	15.73	0.38	15.83	0.45
5	1	15.95	0.59	15.78	0.50	15.78	0.47	15.81	0.48	15.75	0.34
	2	16.00	0.53	15.83	0.50	15.69	0.47	15.81	0.50	15.86	0.39
	3	15.98	0.56	15.70	0.50	15.75	0.50	15.72	0.48	15.88	0.42
	4	-	-	15.89	0.48	15.80	0.52	15.86	0.48	15.84	0.52
6	1	15.89	0.52	15.77	0.50	15.78	0.41	15.84	0.45	15.81	0.42
	2	15.83	0.38	15.88	0.52	15.84	0.47	15.84	0.48	15.80	0.41
	3	15.95	0.42	15.78	0.44	15.86	0.44	15.77	0.41	15.80	0.44
	4	-	-	15.91	0.48	15.72	0.47	15.66	0.39	15.80	0.42
7	1	15.86	0.50	15.88	0.55	15.72	0.44	15.89	0.44	16.00	0.53
	2	15.88	0.50	15.80	0.45	15.84	0.50	15.75	0.44	15.88	0.55
	3	15.86	0.47	15.86	0.78	15.79	0.50	15.84	0.48	15.77	0.47
	4	-	-	15.91	0.47	15.81	0.44	15.84	0.50	15.81	0.52

Table A-8: CMU Specimen Result Summary

Test Period	Relative Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strength Coefficient of Variation
#	days	#	psi	MPa	psi	MPa	psi	%
1	14	1	4063.0	25.4	3683.0	2.3	338.1	9.2
		2	3570.9					
		3	3415.2					
2	28	1	3076.4	23.3	3384.5	4.0	576.4	17.0
		2	3027.6					
		3	4049.5					
3	42	1	NA	26.3	3811.6	0.5	68.5	1.8
		2	3846.6					
		3	3855.6					
		4	3732.6					
4	56	1	3787.5	26.6	3859.0	2.6	372.6	9.7
		2	3480.9					
		3	4373.0					
		4	3794.6					
5	90	1	4127.1	27.9	4050.4	1.1	156.3	3.9
		2	4198.8					
		3	4037.6					
		4	3837.9					

Table A-9: Hollow Prism Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	3116.3	22.68	3289.4	1.04	150.3	4.569
	2	3364.7					
	3	3387.1					
28	1	3191.4	19.64	2848.5	1.65	239.6	8.411
	2	2688.6					
	3	2835.5					
	4	2678.6					
42	1	2834.9	19.26	2793.3	3.14	455.8	16.317
	2	3105.5					
	3	2136.1					
	4	3096.6					
56	1	3060.3	23.05	3343.4	1.41	204.3	6.110
	2	3418.8					
	3	3352.8					
	4	3541.6					
90	1	3854.3	24.74	3588.3	3.27	473.7	13.2
	2	3618.4					
	3	2912.2					
	4	3968.3					

Table A-10: Prism Type 1 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	3000.6	22.12	3208.0	1.25	181.2	5.649
	2	3335.7					
	3	3287.8					
28	1	3066.4	20.05	2908.3	0.91	131.8	4.533
	2	2776.4					
	3	2826.6					
	4	2963.9					
42	1	3459.2	24.85	3603.9	1.51	218.9	6.074
	2	3718.9					
	3	3385.1					
	4	3852.3					
56	1	3789.7	26.20	3799.3	1.85	268.6	7.069
	2	4181.9					
	3	3625.0					
	4	3600.5					
90	1	3553.7	25.52	3701.6	1.29	187.4	5.1
	2	3578.8					
	3	3710.8					
	4	3963.0					

Table A-11: Prism Type 2 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	3000.6	22.12	3208.0	1.25	181.2	5.649
	2	3335.7					
	3	3287.8					
28	1	2348.0	16.40	2379.3	0.71	103.3	4.340
	2	2246.7					
	3	2461.2					
	4	2461.2					
42	1	2702.7	20.46	2968.1	1.35	196.0	6.605
	2	3002.2					
	3	3175.7					
	4	2991.7					
56	1	2756.8	20.94	3037.1	1.77	257.4	8.475
	2	3370.0					
	3	2947.8					
	4	3074.0					
90	1	3168.9	24.17	3506.1	1.63	236.7	6.8
	2	3722.8					
	3	3573.3					
	4	3559.5					

Table A-12: Prism Type 3 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	2184.3	14.78	2143.3	2.91	422.5	19.714
	2	1701.8					
	3	2543.9					
28	1	2279.8	15.59	2261.8	0.82	118.5	5.238
	2	2420.3					
	3	2150.3					
	4	2196.9					
42	1	2708.0	18.00	2610.7	0.87	126.1	4.828
	2	2689.6					
	3	2613.3					
	4	2431.9					
56	1	2360.5	17.58	2549.1	1.77	257.1	10.086
	2	2323.9					
	3	2641.0					
	4	2870.9					
90	1	3005.6	21.51	3119.7	0.91	132.3	4.2
	2	3219.9					
	3	3248.0					
	4	3005.6					

Table A-13: Prism Type 4 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	2184.3	14.78	2143.3	2.91	422.5	19.714
	2	1701.8					
	3	2543.9					
28	1	2266.7	14.44	2094.5	1.21	176.0	8.403
	2	2224.0					
	3	1966.3					
	4	1921.0					
42	1	2457.8	15.47	2244.3	2.86	415.2	18.498
	2	1883.1					
	3	2724.5					
	4	1912.0					
56	1	2458.3	18.43	2673.2	1.09	158.4	5.927
	2	2738.7					
	3	2830.7					
	4	2665.3					
90	1	2986.6	18.56	2691.7	2.49	361.3	13.4
	2	2194.9					
	3	2655.8					
	4	2929.5					

Table A-14: Prism Type 5 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	2925.1	21.17	3070.7	1.06	153.7	5.004
	2	3055.6					
	3	3231.3					
28	1	3514.1	22.08	3202.6	2.26	327.2	10.216
	2	3445.4					
	3	2849.7					
	4	3001.1					
42	1	3691.7	26.87	3897.5	1.30	188.6	4.839
	2	3938.8					
	3	4062.0					
	4	NA					
56	1	3650.4	25.48	3695.4	1.04	150.5	4.073
	2	3511.4					
	3	3755.4					
	4	3864.2					
90	1	4262.1	28.42	4122.7	1.18	170.9	4.1
	2	3924.6					
	3	4035.3					
	4	4268.7					

Table A-15: Prism Type 6 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	2459.0	18.81	2727.6	1.61	233.1	8.548
	2	2845.6					
	3	2878.1					
28	1	2621.3	18.50	2682.7	0.66	96.3	3.589
	2	2751.0					
	3	2777.6					
	4	2580.9					
42	1	3671.8	24.01	3482.3	1.25	181.8	5.220
	2	3294.9					
	3	3362.7					
	4	3599.7					
56	1	3680.9	22.97	3331.1	2.21	320.2	9.613
	2	3229.8					
	3	2938.4					
	4	3475.0					
90	1	3429.1	25.00	3625.7	0.96	139.9	3.9
	2	3725.9					
	3	3725.9					
	4	3621.7					

Table A-16: Prism Type 7 Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	2677.0	18.02	2613.1	0.50	72.5	2.773
	2	2628.0					
	3	2534.4					
28	1	2258.6	15.73	2281.3	0.50	71.8	3.149
	2	2384.1					
	3	2265.8					
	4	2216.8					
42	1	3123.1	19.44	2818.8	2.77	401.9	14.258
	2	2868.2					
	3	2237.6					
	4	3046.4					
56	1	3141.8	22.37	3244.5	1.31	190.0	5.857
	2	3033.5					
	3	3356.0					
	4	3446.6					
90	1	3364.5	24.03	3484.6	0.82	119.0	3.4
	2	3437.3					
	3	3491.6					
	4	3645.0					

Table A-17 Mortar Cube Specimen Result Summary

Age	Specimen	Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	MPa	psi	MPa	psi	%
14	1	3157.5	18.02	2614.2	3.32	481.0	18.402
	2	2442.5					
	3	2242.5					
28	1	3090.0	19.12	2773.3	2.95	427.2	15.402
	2	2942.5					
	3	2287.5					
42	1	3522.5	23.59	3421.7	3.20	464.5	13.576
	2	3827.5					
	3	2915.0					
56	1	2905.0	18.39	2667.5	3.15	457.6	17.154
	2	2957.5					
	3	2140.0					
90	1	3015.0	21.72	3150.0	3.99	579.4	18.4
	2	3785.0					
	3	2650.0					

Table A-18: Grout Type 1 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	3020.9	3353.2	22.0	3188.7	3.3	479.5	15.037
	2	2386.1	2648.6					
	3	3211.1	3564.3					
28	1	3288.3	3650.0	23.4	3396.5	1.5	219.7	6.467
	2	2950.6	3275.2					
	3	2940.7	3264.2					
42	1	3041.7	3376.3	26.9	3897.7	3.9	567.7	14.565
	2	4056.3	4502.5					
	3	3436.4	3814.4					
56	1	4186.0	4646.5	25.1	3637.8	10.2	1472.9	40.490
	2	3714.6	4123.2					
	3	1688.5	1874.2					
		3520.0	3907.2					
90	1	4204.3	4666.8	32.1	4656.6	0.7	102.0	2.2
	2	4171.7	4630.5					
	3	4091.4	4541.5					
	4	4313.3	4787.7					

Table A-19: Grout Type 2 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	1119.0	1242.1	9.0	1305.2	0.4	61.6	4.720
	2	1230.0	1365.3					
	3	1178.5	1308.1					
28	1	1967.2	2183.6	14.4	2082.3	1.9	278.3	13.364
	2	2068.3	2295.8					
	3	1592.4	1767.6					
42	1	1255.2	1393.3	17.7	2560.0	6.0	865.4	33.805
	2	3008.1	3338.9					
	3	2193.5	2434.8					
	4	2768.4	3072.9					
56	1	3067.5	3404.9	23.0	3333.7	0.7	107.2	3.216
	2	2893.7	3212.0					
	3	3099.7	3440.6					
	4	2952.6	3277.4					
90	1	4686.1	5201.6	28.4	4123.1	5.7	820.5	19.9
	2	3699.3	4106.2					
	3	3580.9	3974.8					
	4	2891.7	3209.8					

Table A-20: Grout Type 3 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	933.9	1036.6	7.6	1103.1	1.8	265.5	24.066
	2	1257.2	1395.5					
	3	790.3	877.2					
28	1	1832.6	2034.1	11.9	1720.5	3.2	466.5	27.113
	2	1067.1	1184.4					
	3	1750.4	1942.9					
42	1	2313.8	2568.4	17.8	2583.6	0.1	13.9	0.537
	2	2331.2	2587.6					
	3	2322.3	2577.7					
	4	2343.1	2600.8					
56	1	2302.0	2555.2	18.4	2672.2	1.3	190.0	7.109
	2	2493.6	2767.9					
	3	2603.0	2889.3					
	4	2231.2	2476.6					
90	1	3288.8	3650.6	24.2	3503.1	1.8	262.0	7.5
	2	3087.8	3427.4					
	3	2856.5	3170.8					
	4	3390.8	3763.8					

Table A-21: Grout Type 4 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	515.9	572.7	4.0	582.8	0.4	53.2	9.130
	2	482.3	535.3					
	3	576.9	640.3					
28	1	820.0	910.2	6.4	925.6	0.9	129.8	14.029
	2	724.4	804.1					
	3	957.1	1062.4					
42	1	1262.6	1401.5	11.0	1597.3	1.0	150.2	9.406
	2	1460.7	1621.4					
	3	1440.9	1599.4					
	4	1591.9	1767.0					
56	1	1556.3	1727.5	12.4	1799.6	1.0	149.0	8.281
	2	1534.0	1702.7					
	3	1573.6	1746.7					
	4	1821.2	2021.5					
90	1	2236.1	2482.1	17.2	2500.8	0.4	64.8	2.6
	2	2186.1	2426.6					
	3	2326.2	2582.1					
	4	2263.3	2512.3					

Table A-22: Grout Type 5 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	2810.5	3119.6	18.4	2662.2	3.9	562.1	21.114
	2	1833.1	2034.7					
	3	2551.5	2832.2					
28	1	1521.1	1688.4	17.7	2572.9	5.3	766.5	29.790
	2	2692.6	2988.8					
	3	2740.2	3041.6					
42	1	4298.4	4771.2	31.6	4582.3	1.3	182.6	3.986
	2	3988.5	4427.2					
	3	4240.0	4706.4					
	4	3986.0	4424.4					
56	1	3710.2	4118.3	31.3	4539.0	2.6	372.8	8.214
	2	4456.4	4946.6					
	3	4268.2	4737.7					
	4	3922.1	4353.5					
90	1	4828.2	5359.3	35.0	5079.6	5.2	749.1	14.7
	2	5039.7	5594.0					
	3	3573.5	3966.6					
	4	4863.4	5398.4					

Table A-23: Grout Type 6 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	2579.2	2863.0	18.7	2713.7	0.9	131.6	4.850
	2	2355.4	2614.5					
	3	2399.5	2663.5					
28	1	2055.4	2281.5	17.6	2556.1	2.0	297.3	11.630
	2	2265.8	2515.1					
	3	2587.2	2871.8					
42	1	3180.4	3530.2	23.6	3429.6	1.4	199.4	5.814
	2	3075.9	3414.2					
	3	3258.1	3616.5					
	4	2844.6	3157.6					
56	1	3251.2	3608.8	26.3	3817.8	1.5	216.6	5.673
	2	3709.2	4117.2					
	3	3362.1	3731.9					
	4	3435.4	3813.3					
90	1	3991.4	4430.5	30.6	4435.6	0.9	135.2	3.0
	2	3915.7	4346.4					
	3	4169.7	4628.3					
	4	3907.2	4337.0					

Table A-24: Grout Type 7 Specimen Result Summary

Age	Specimen	Measured Compressive Strength	Amplified Compressive Strength	Average Compressive Strength		Compressive Strength Standard Deviation		Compressive Strenght Coefficient of Variation
days	#	psi	psi	MPa	psi	MPa	psi	%
14	1	1418.1	1574.1	10.1	1459.4	0.9	129.1	8.845
	2	1188.9	1319.6					
	3	1337.4	1484.5					
28	1	1709.8	1897.8	11.8	1717.6	1.2	179.5	10.448
	2	1545.9	1715.9					
	3	1386.4	1538.9					
42	1	1848.9	2052.3	14.9	2161.5	1.0	141.2	6.531
	2	2031.6	2255.1					
	3	2080.1	2308.9					
	4	1828.6	2029.7					
56	1	2175.7	2415.0	16.7	2428.4	0.8	111.4	4.589
	2	2249.5	2496.9					
	3	2050.9	2276.5					
	4	2274.7	2524.9					
90	1	2481.7	2754.7	18.3	2657.8	0.7	95.9	3.6
	2	2400.0	2664.0					
	3	2275.7	2526.0					
	4	2420.3	2686.5					

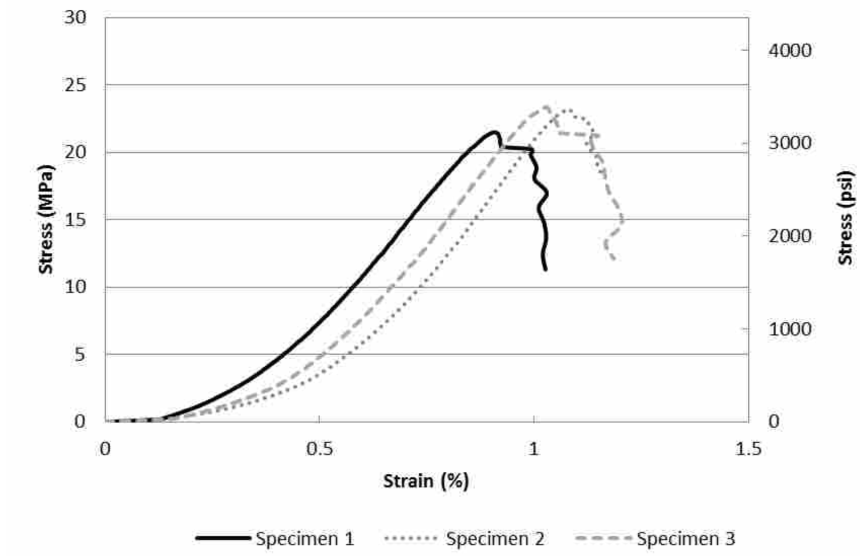


Figure A-1: Hollow Prism Specimens 1-3 @ 14 Days Stress vs. Strain

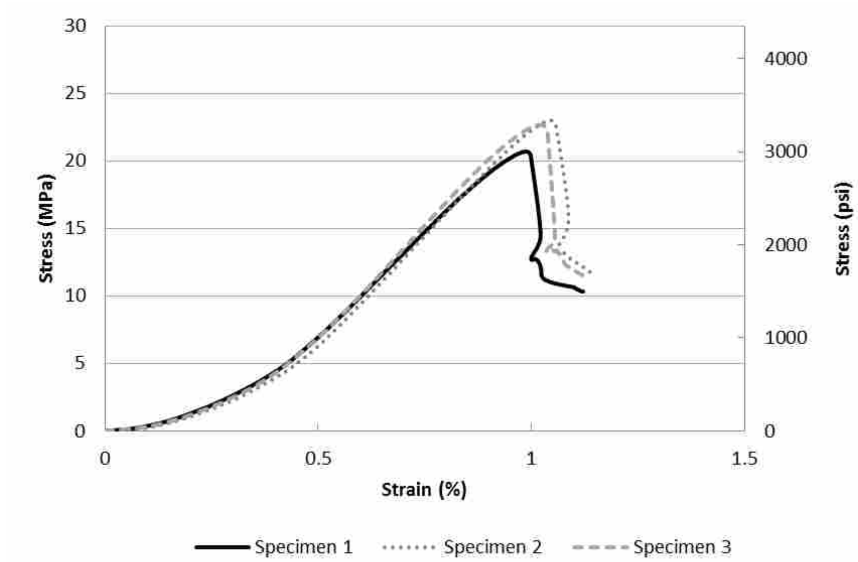


Figure A-2: Prism Specimens 1-3 Type 1 @ 14 Days Stress vs. Strain

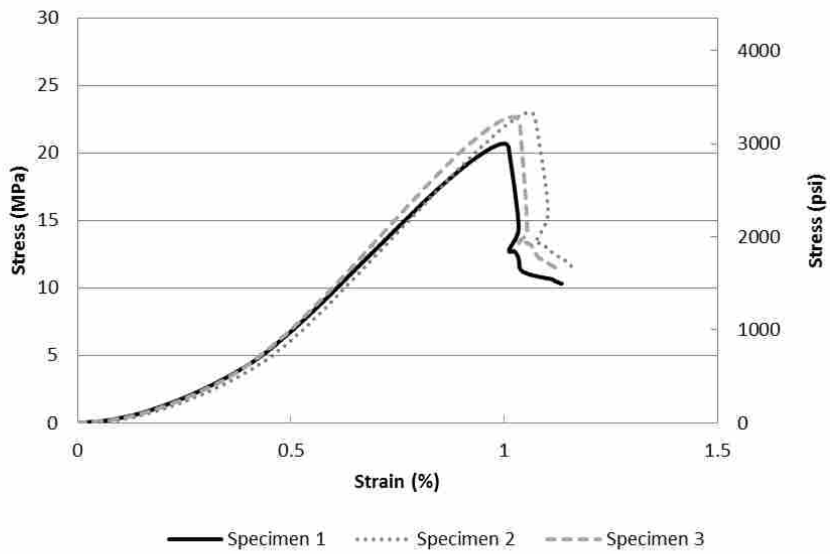


Figure A-3: Prism Specimens 1-3 Type 2 @ 14 Days Stress vs. Strain

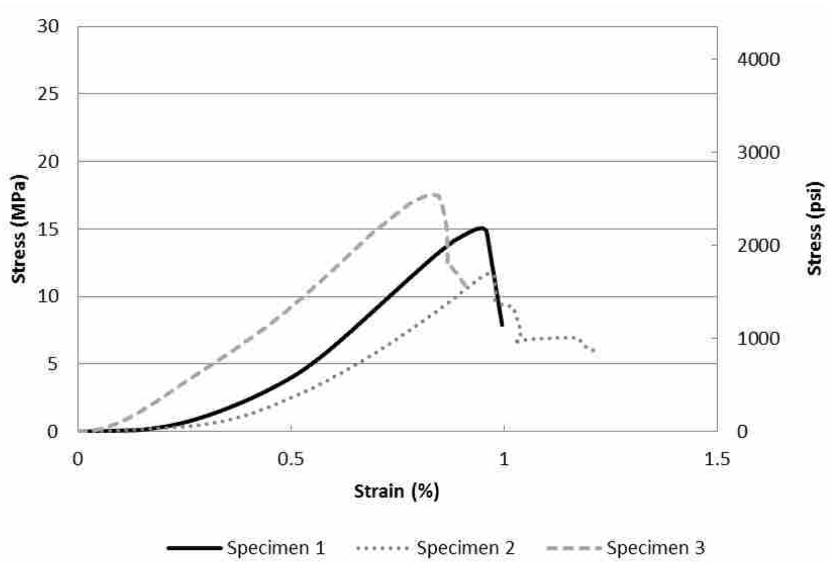


Figure A-4: Prism Specimens 1-3 Type 3 @ 14 Days Stress vs. Strain

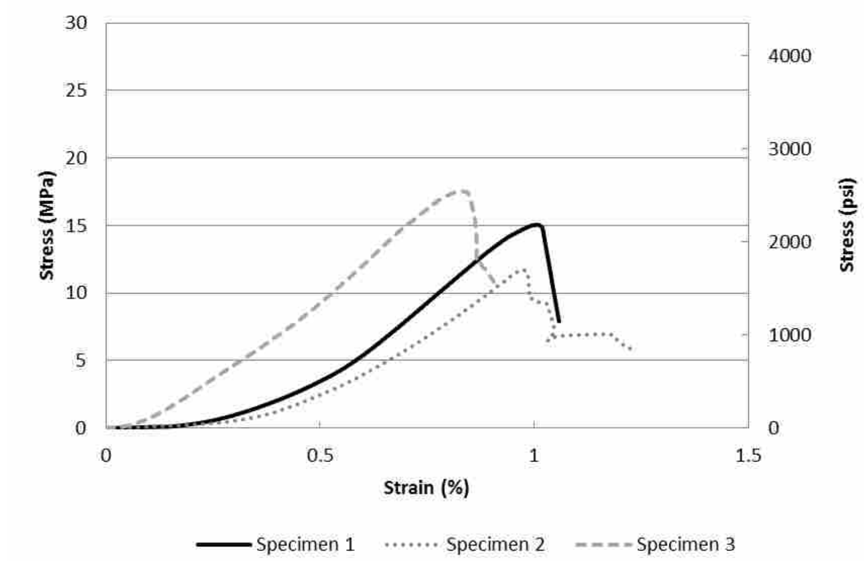


Figure A-5: Prism Specimens 1-3 Type 4 @ 14 Days Stress vs. Strain

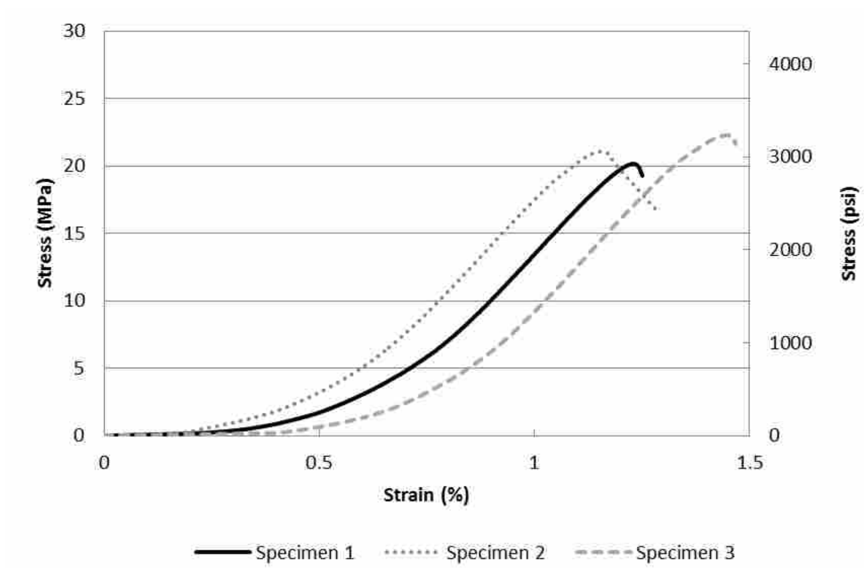


Figure A-6: Prism Specimens 1-3 Type 5 @ 14 Days Stress vs. Strain

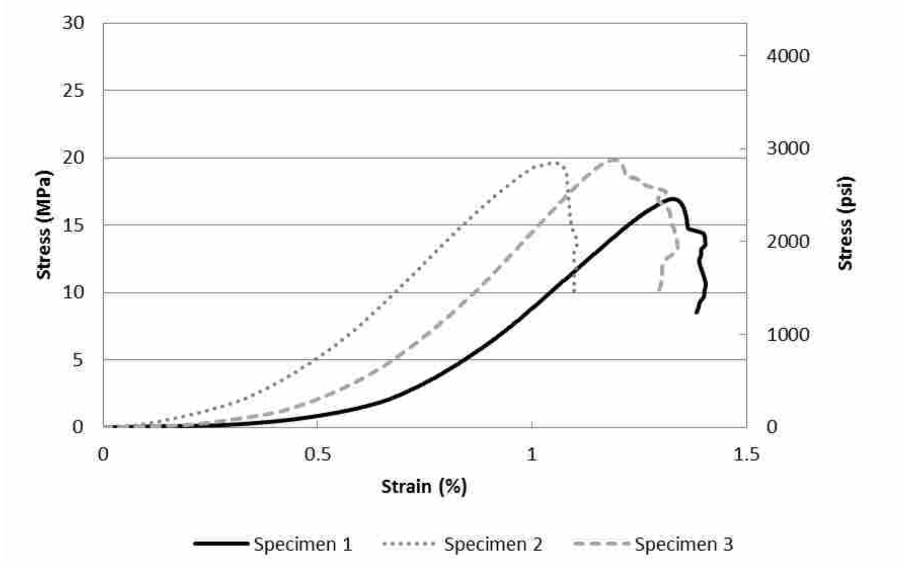


Figure A-7: Prism Specimens 1-3 Type 6 @ 14 Days Stress vs. Strain

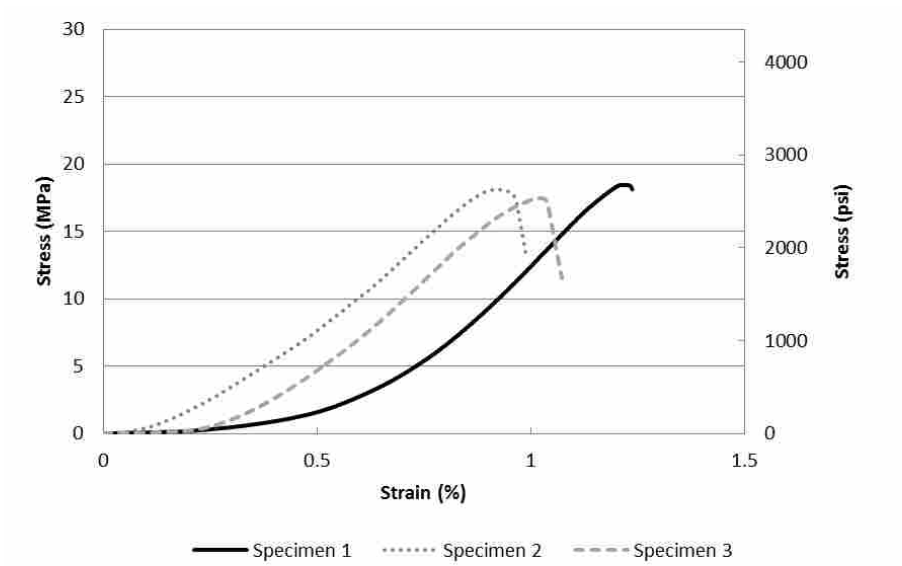


Figure A-8: Prism Specimens 1-3 Type 7 @ 14 Days Stress vs. Strain

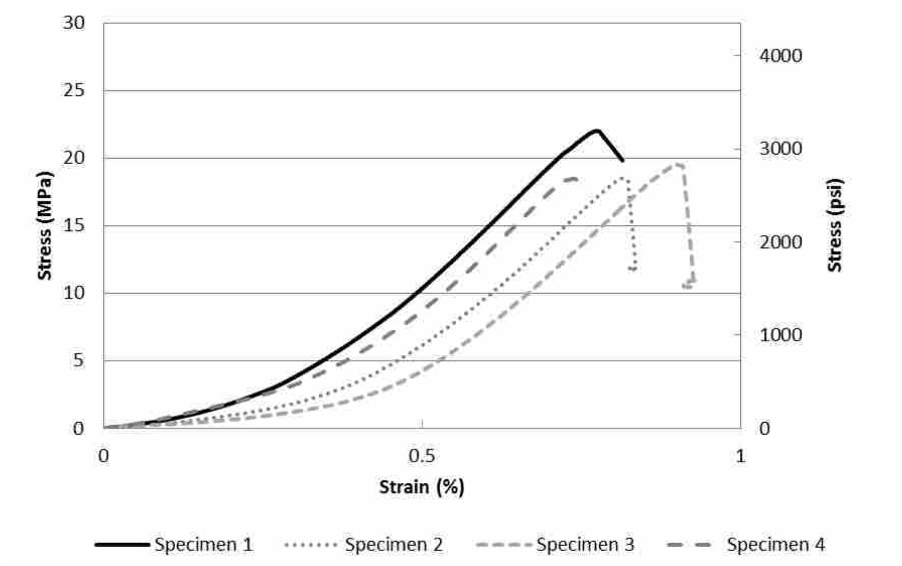


Figure A-9: Hollow Prism Specimens 1-4 @ 28 Days Stress vs. Strain

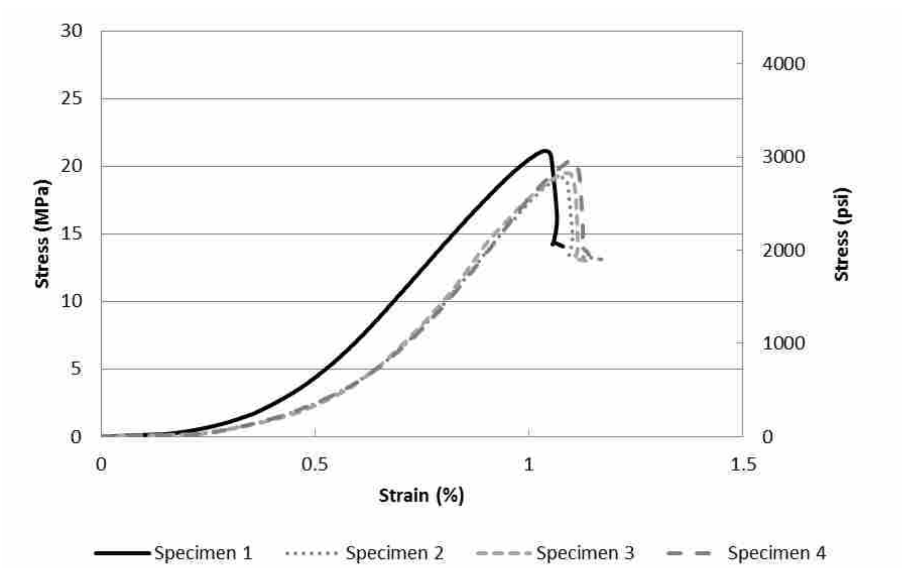


Figure A-10: Prism Specimens 1-4 Type 1 @ 28 Days Stress vs. Strain

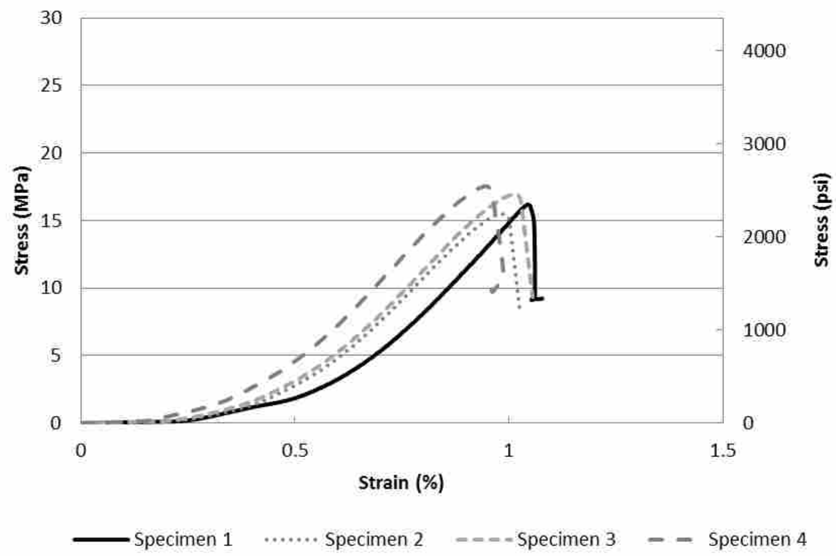


Figure A-11: Prism Specimens 1-4 Type 2 @ 28 Days Stress vs. Strain

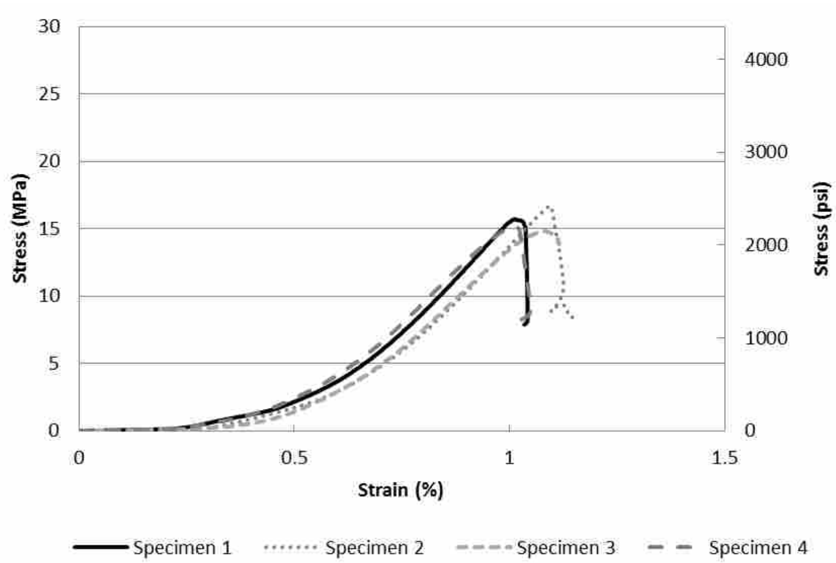


Figure A-12: Prism Specimens 1-4 Type 3 @ 28 Days Stress vs. Strain

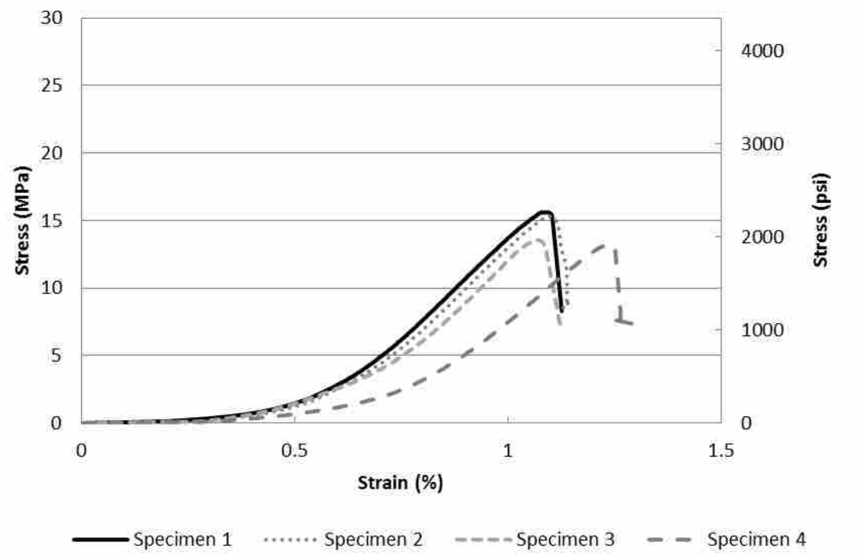


Figure A-13: Prism Specimens 1-4 Type 4 @ 28 Days Stress vs. Strain

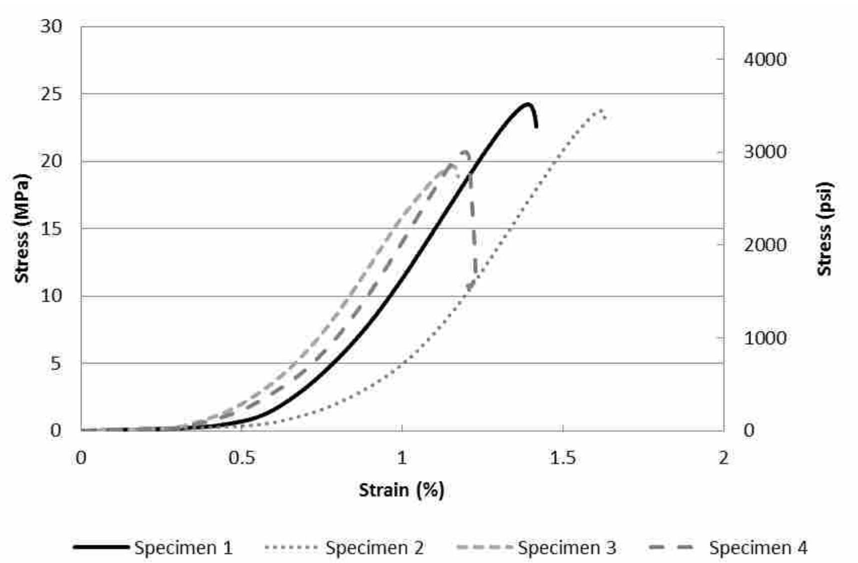


Figure A-14: Prism Specimens 1-4 Type 5 @ 28 Days Stress vs. Strain

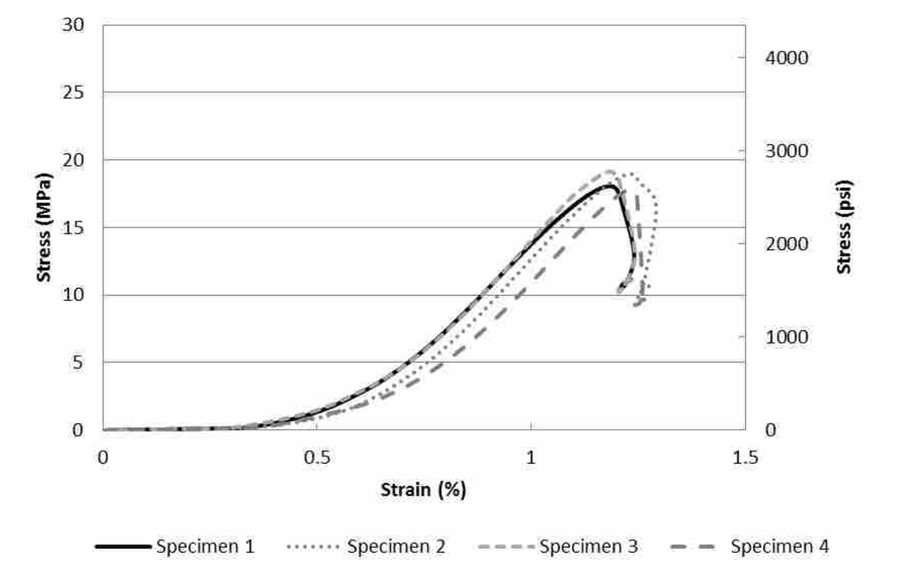


Figure A-15: Prism Specimens 1-4 Type 6 @ 28 Days Stress vs. Strain

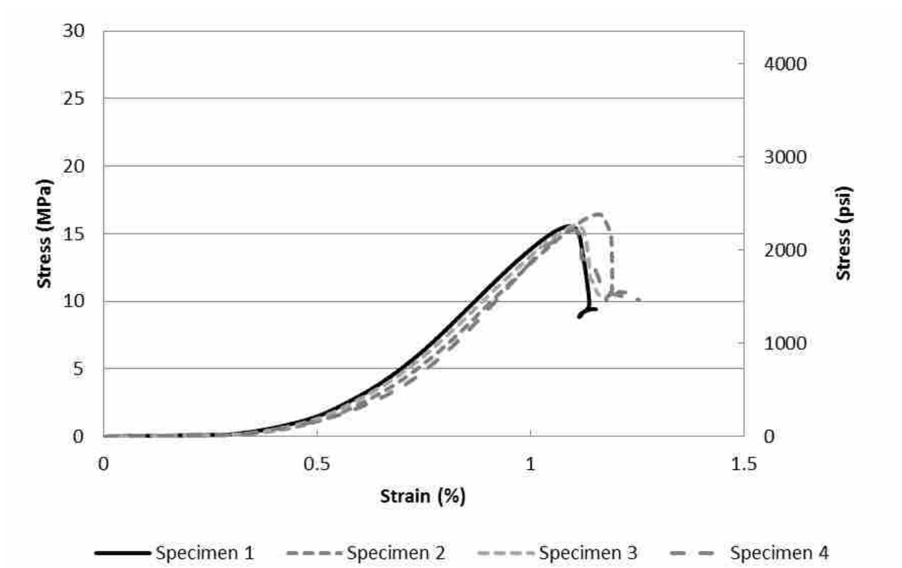


Figure A-16: Prism Specimens 1-4 Type 7 @ 28 Days Stress vs. Strain

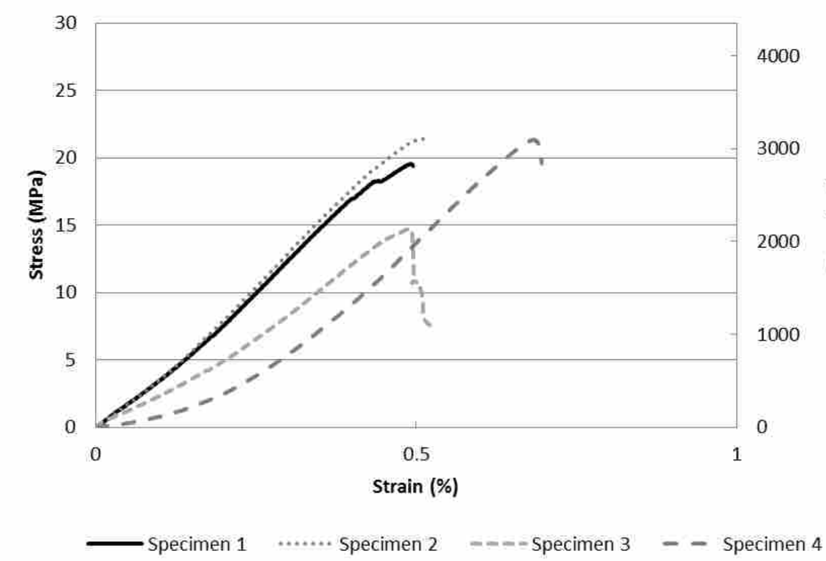


Figure A-17: Hollow Prism Specimens 1-4 @ 42 Days Stress vs. Strain

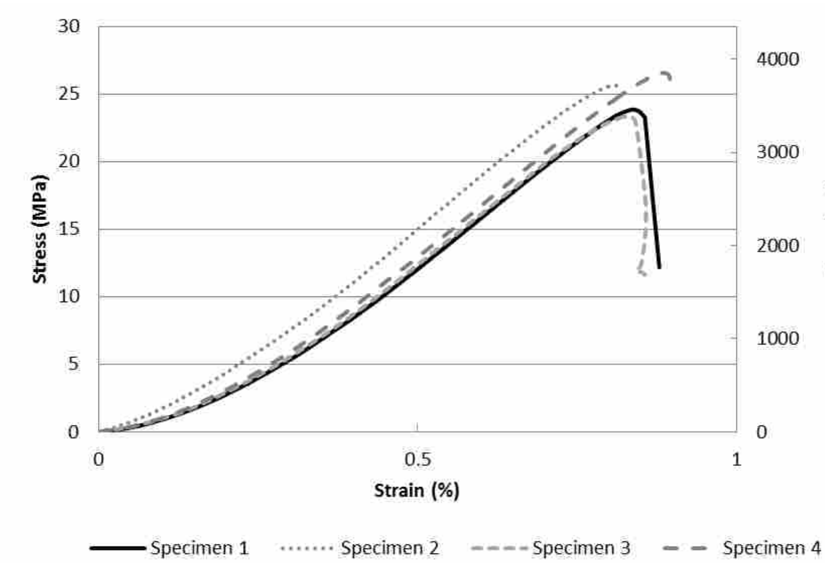


Figure A-18: Prism Specimens 1-4 Type 1 @ 42 Days Stress vs. Strain

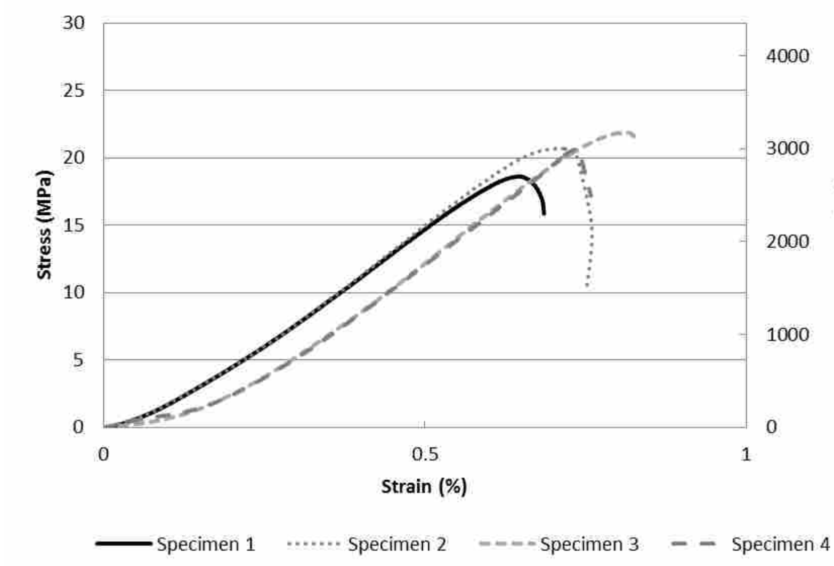


Figure A-19: Prism Specimens 1-4 Type 2 @ 42 Days Stress vs. Strain

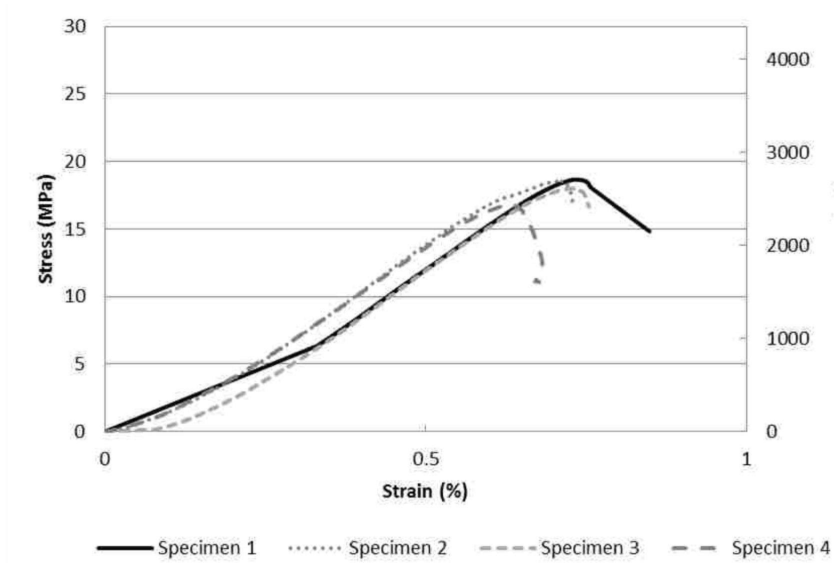


Figure A-20: Prism Specimens 1-4 Type 3 @ 42 Days Stress vs. Strain

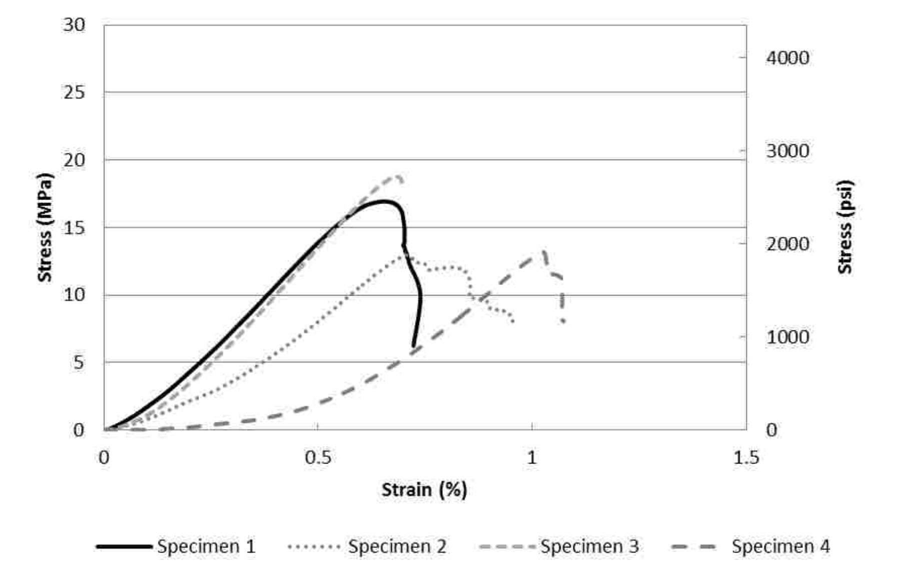
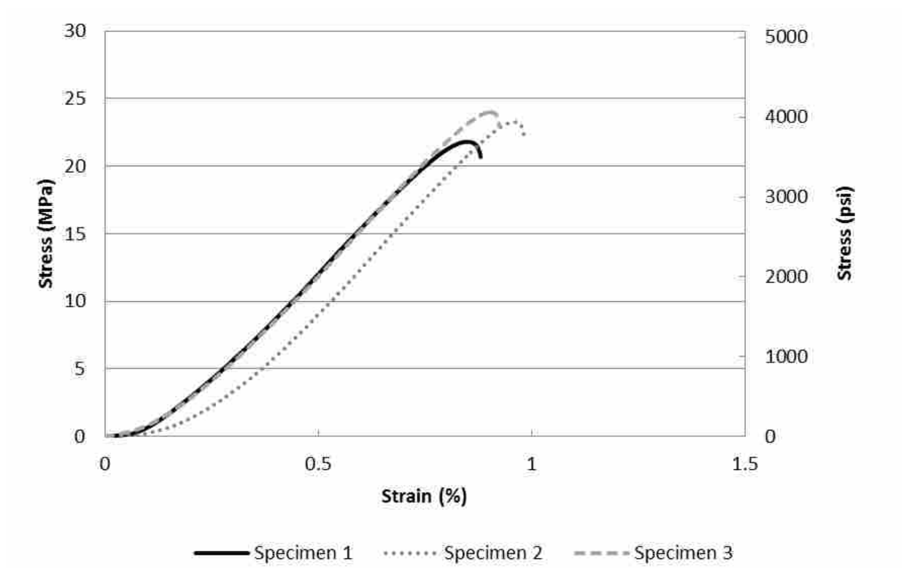


Figure A-21: Prism Specimens 1-4 Type 4 @ 42 Days Stress vs. Strain



***Specimen 4 Not Available**

Figure A-22: Prism Specimens 1-3 Type 5 @ 42 Days Stress vs. Strain

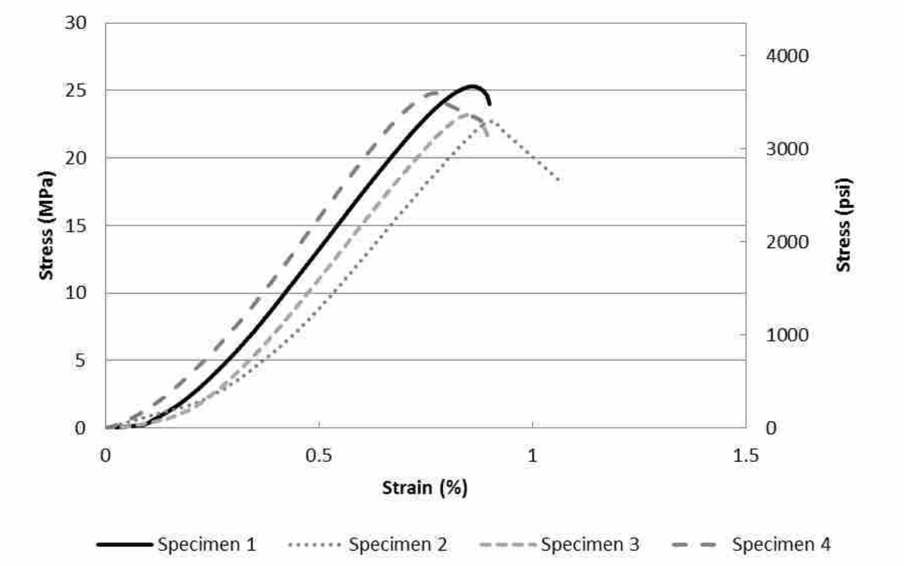


Figure A-23: Prism Specimens 1-4 Type 6 @ 42 Days Stress vs. Strain

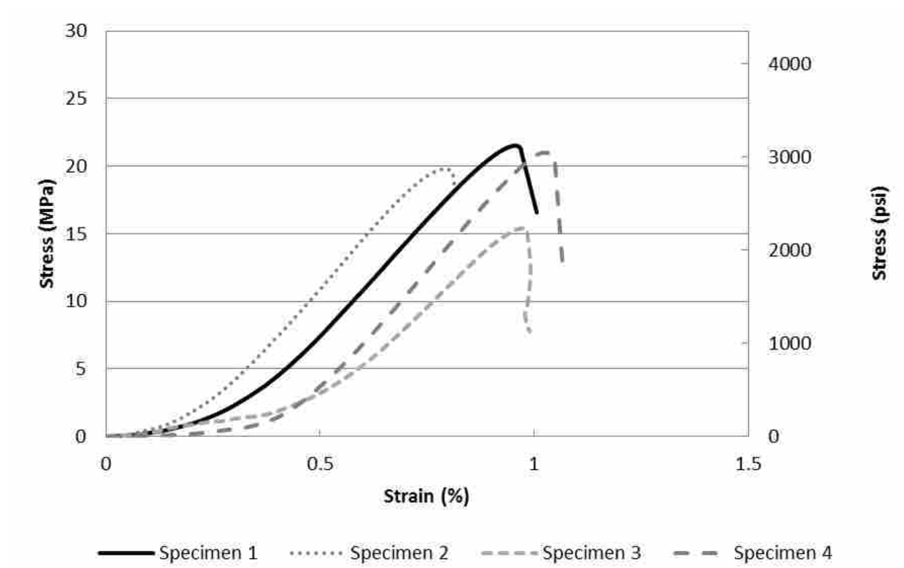


Figure A-24: Prism Specimens 1-4 Type 7 @ 42 Days Stress vs. Strain

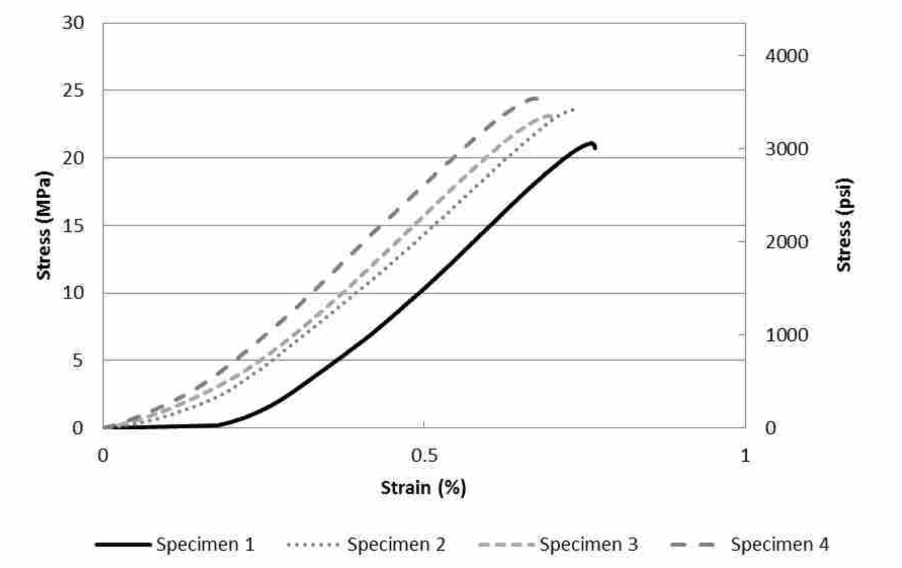


Figure A-25: Hollow Prism Specimens 1-4 @ 56 Days Stress vs. Strain

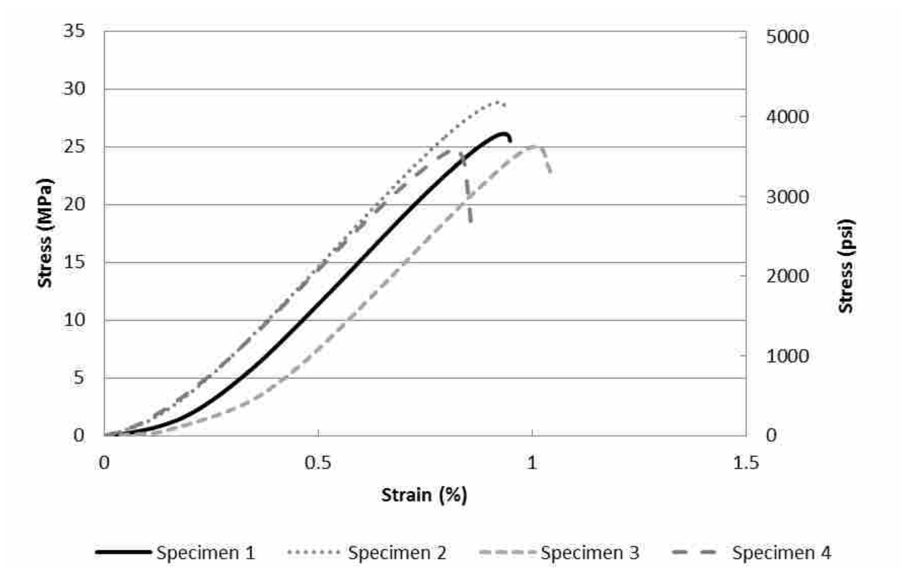


Figure A-26: Prism Specimens 1-4 Type 1 @ 56 Days Stress vs. Strain

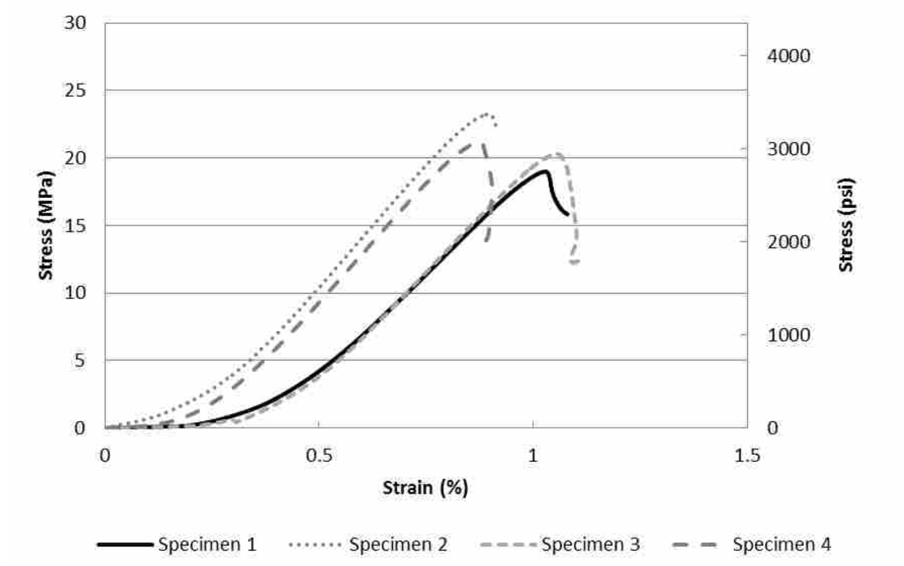


Figure A-27: Prism Specimens 1-4 Type 2 @ 56 Days Stress vs. Strain

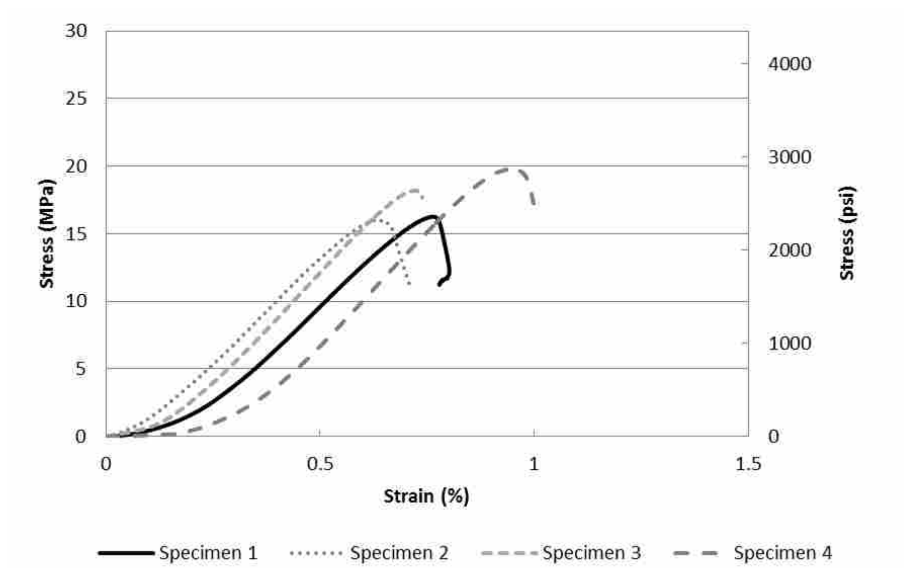


Figure A-28: Prism Specimens 1-4 Type 3 @ 56 Days Stress vs. Strain

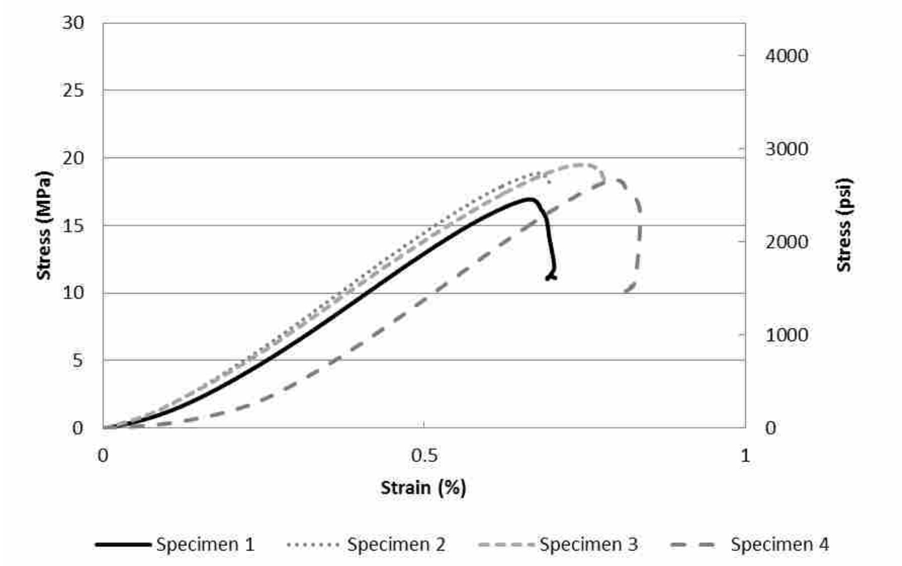


Figure A-29: Prism Specimens 1-4 Type 4 @ 56 Days Stress vs. Strain

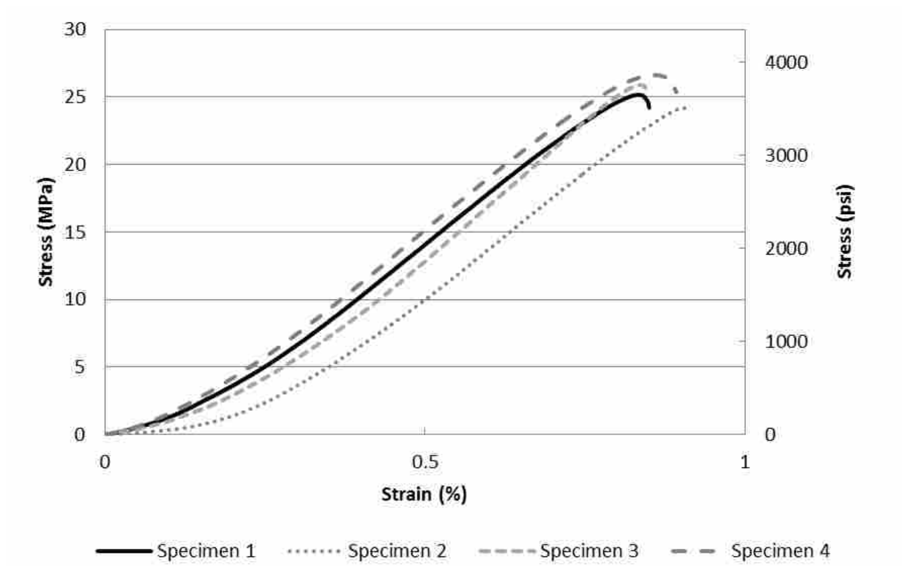


Figure A-30: Prism Specimens 1-4 Type 5 @ 56 Days Stress vs. Strain

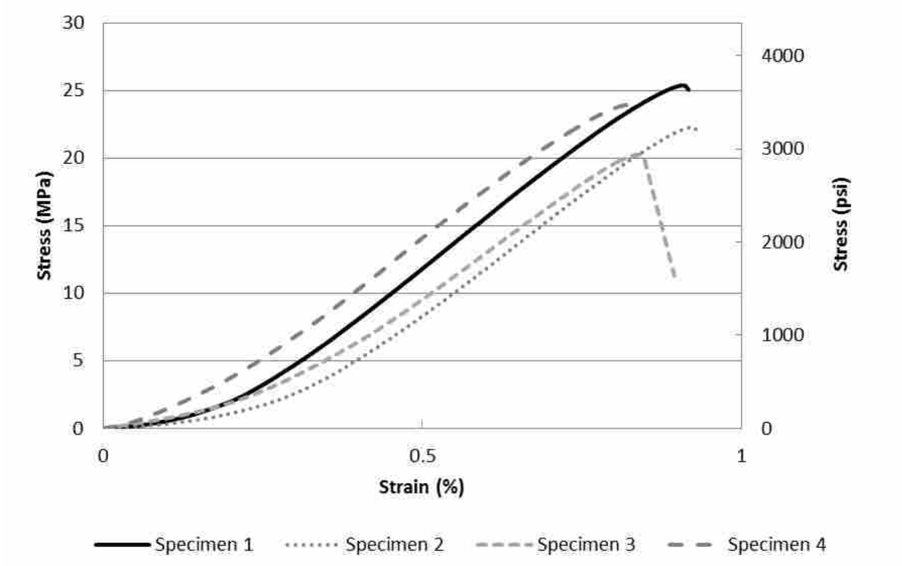


Figure A-31: Prism Specimens 1-4 Type 6 @ 56 Days Stress vs. Strain

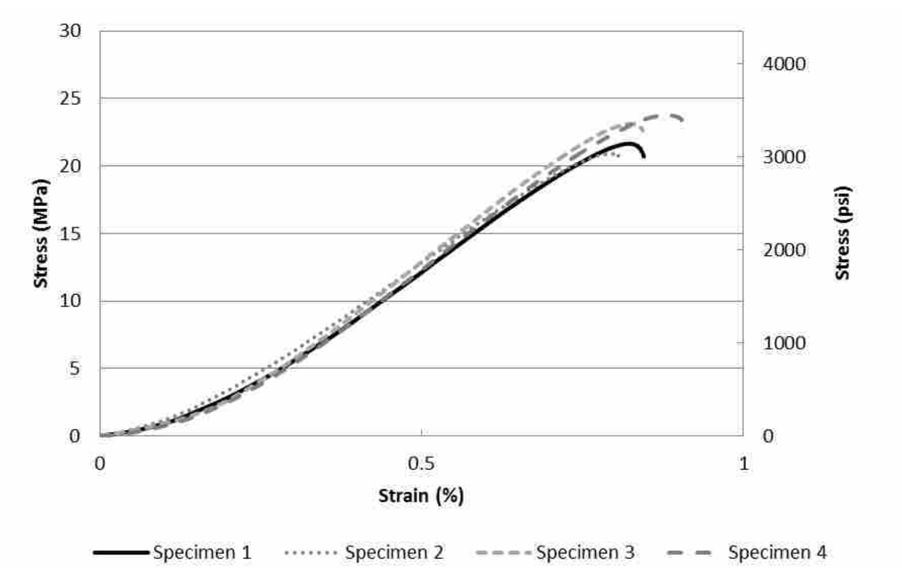


Figure A-32: Prism Specimens 1-4 Type 7 @ 56 Days Stress vs. Strain

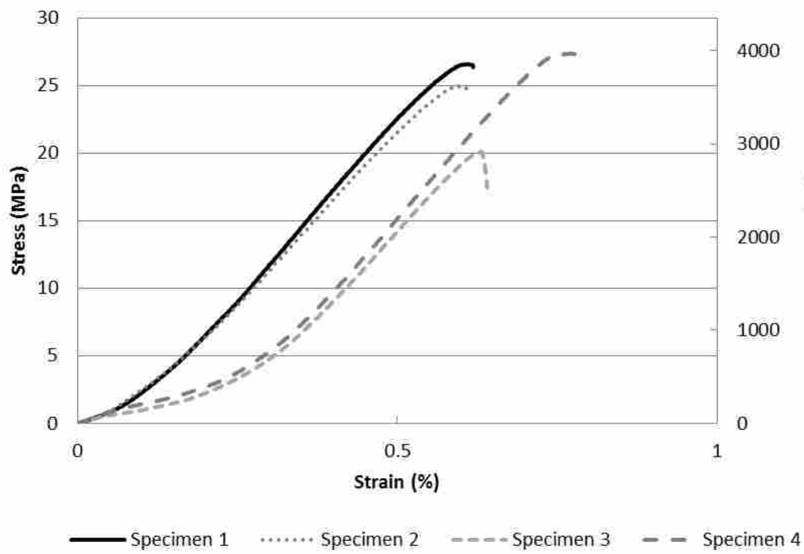


Figure A-33: Hollow Prism Specimens 1-4 @ 90 Days Stress vs. Strain

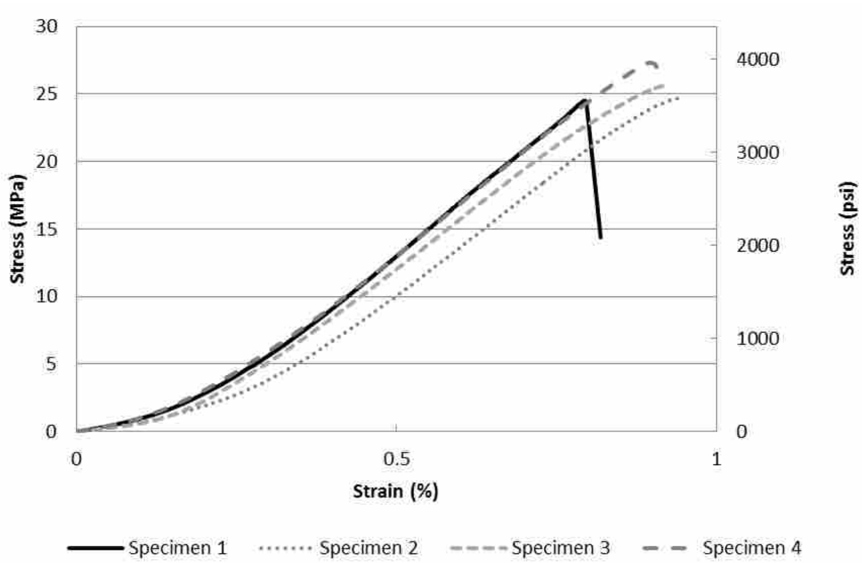


Figure A-34: Prism Specimens 1-4 Type 1 @ 90 Days Stress vs. Strain

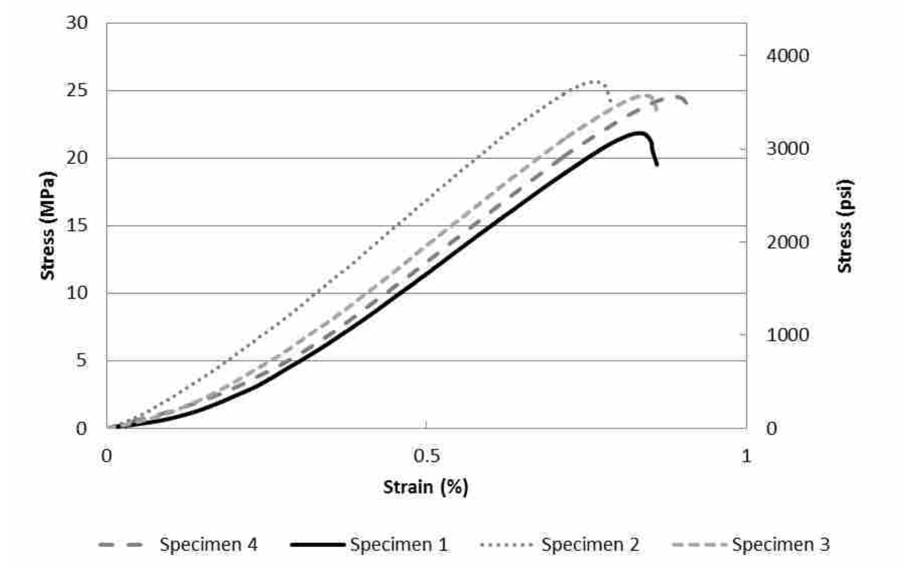


Figure A-35: Prism Specimens 1-4 Type 2 @ 90 Days Stress vs. Strain

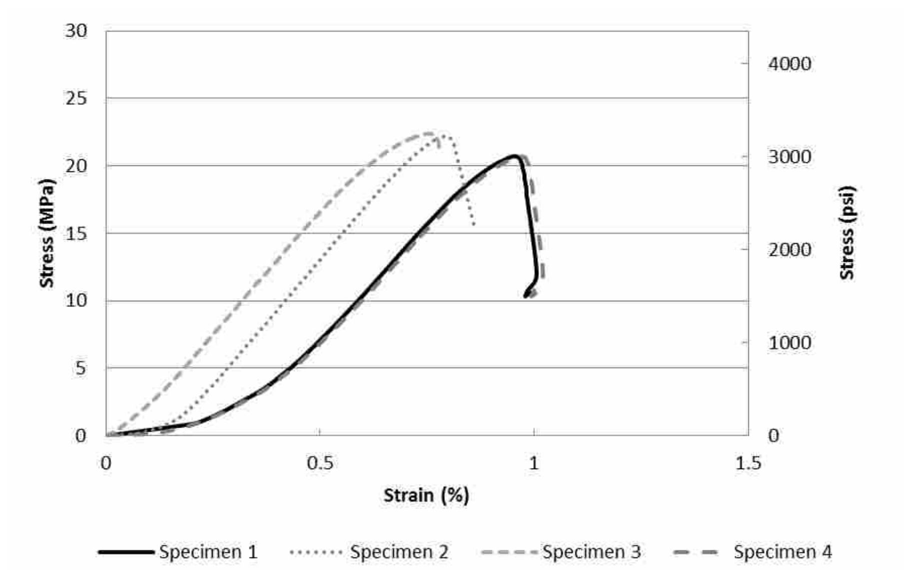


Figure A-36: Prism Specimens 1-4 Type 3 @ 90 Days Stress vs. Strain

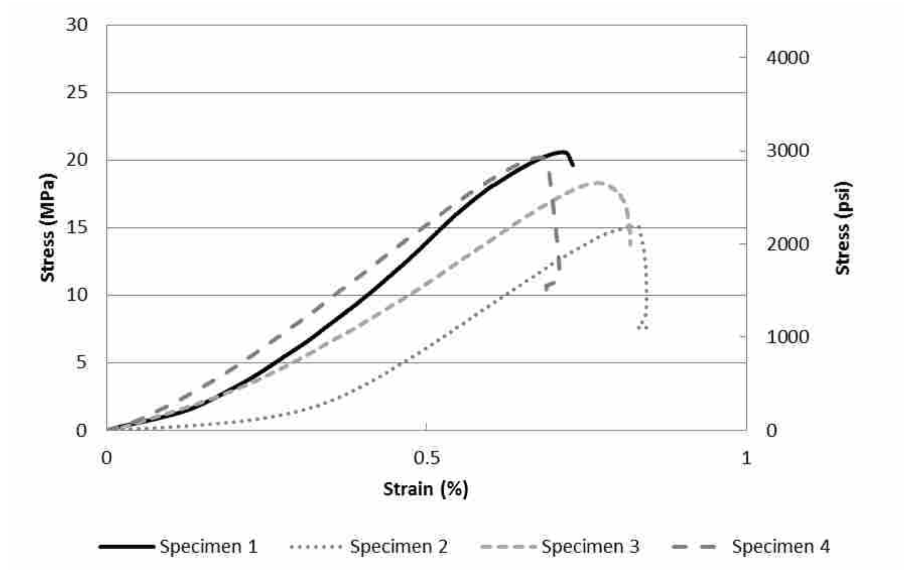


Figure A-37: Prism Specimens 1-4 Type 4 @ 90 Days Stress vs. Strain

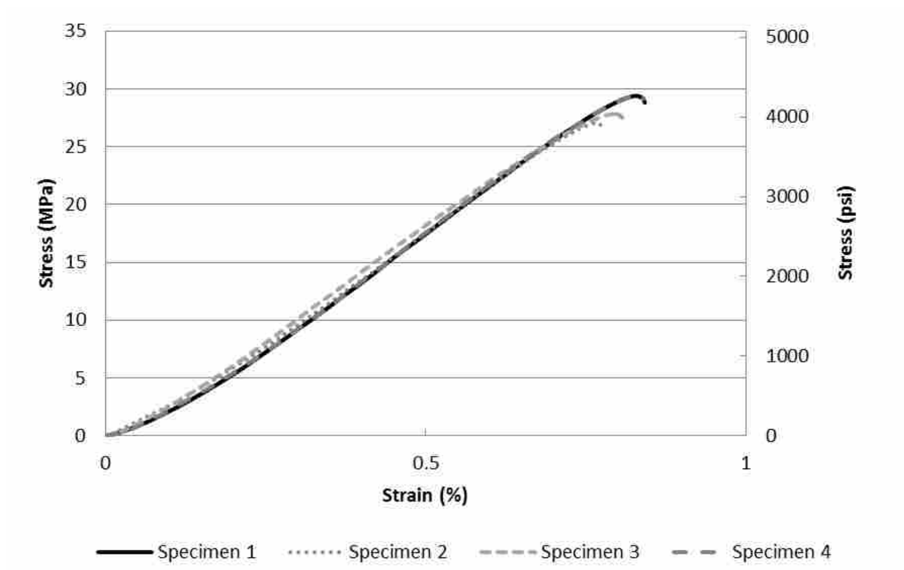


Figure A-38: Prism Specimens 1-4 Type 5 @ 90 Days Stress vs. Strain

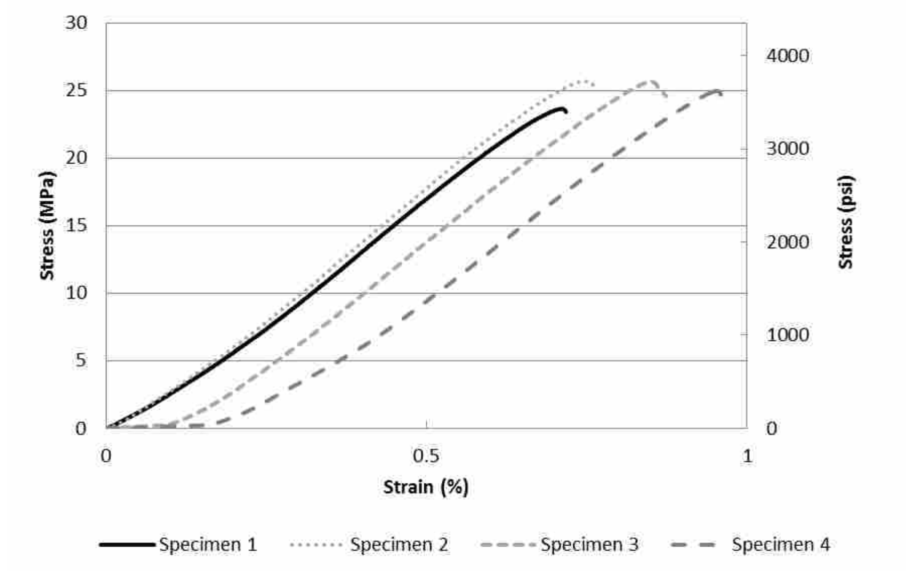


Figure A-39: Prism Specimens 1-4 Type 6 @ 90 Days Stress vs. Strain

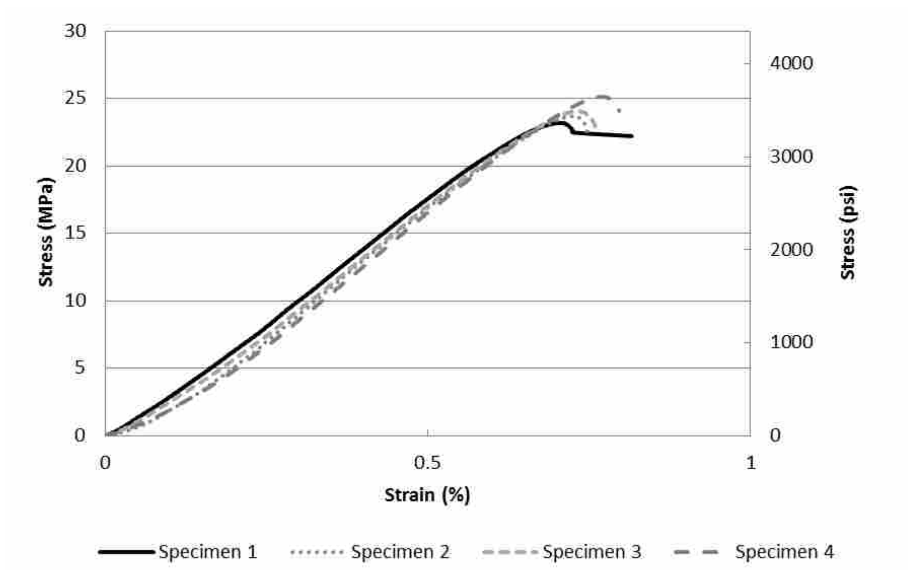


Figure A-40: Prism Specimens 1-4 Type 7 @ 90 Days Stress vs. Strain

Appendix B. Compressive Strength Specimen Pictures

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

Figure B-1: Hollow Prism Specimen 1 @ 14 Days After Failure

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

Figure B-2: Hollow Prism Specimen 2 @ 14 Days After Failure

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

Figure B-3: Hollow Prism Specimen 3 @ 14 Days After Failure

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

Figure B-4: Prism Specimen 1 Type 1 @ 14 Days After Failure

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

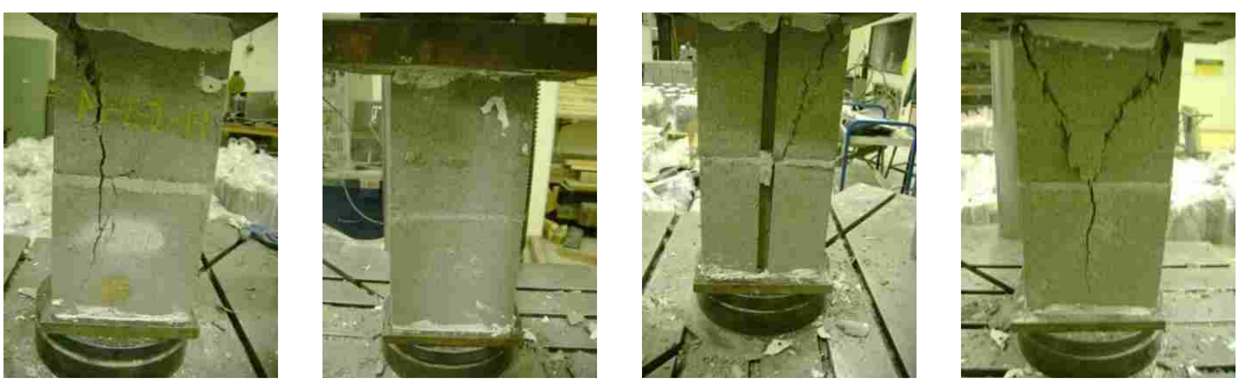
Figure B-5: Prism Specimen 2 Type 1 @ 14 Days After Failure

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

Figure B-6: Prism Specimen 3 Type 1 @ 14 Days After Failure

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

Figure B-7: Prism Specimen 1 Type 2 @ 14 Days After Failure



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

Figure B-8: Prism Specimen 2 Type 2 @ 14 Days After Failure

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

Figure B-9: Prism Specimen 3 Type 2 @ 14 Days After Failure

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

Figure B-10: Prism Specimen 1 Type 3 @ 14 Days After Failure

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

Figure B-11: Prism Specimen 2 Type 3 @ 14 Days After Failure

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

Figure B-12: Prism Specimen 3 Type 3 @ 14 Days After Failure

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

Figure B-13: Prism Specimen 2 Type 4 @ 14 Days After Failure

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

Figure B-14: Prism Specimen 3 Type 4 @ 14 Days After Failure

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

Figure B-15: Prism Specimen 2 Type 5 @ 14 Days After Failure

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

Figure B-16: Prism Specimen 3 Type 5 @ 14 Days After Failure

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

Figure B-17: Prism Specimen 1 Type 6 @ 14 Days After Failure

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

Figure B-18: Prism Specimen 2 Type 6 @ 14 Days After Failure

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

Figure B-19: Prism Specimen 3 Type 6 @ 14 Days After Failure

Not Available

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

Figure B-20: Prism Specimen 1 Type 7 @ 14 Days After Failure

Not Available

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

Figure B-21: Prism Specimen 2 Type 7 @ 14 Days After Failure

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

Figure B-22: Prism Specimen 3 Type 7 @ 14 Days After Failure

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

Figure B-23: Hollow Prism Specimen 1 @ 28 Days After Failure

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

Figure B-24: Hollow Prism Specimen 2 @ 28 Days After Failure

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

Figure B-25: Hollow Prism Specimen 3 @ 28 Days After Failure

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

Figure B-26: Hollow Prism Specimen 4 @ 28 Days After Failure

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

Figure B-27: Prism Specimen 1 Type 1 @ 28 Days After Failure

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

Figure B-28: Prism Specimen 2 Type 1 @ 28 Days After Failure

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

Figure B-29: Prism Specimen 3 Type 1 @ 28 Days After Failure

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

Figure B-30: Prism Specimen 4 Type 1 @ 28 Days After Failure

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

Figure B-31: Prism Specimen 1 Type 2 @ 28 Days After Failure

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

Figure B-32: Prism Specimen 2 Type 2 @ 28 Days After Failure

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

Figure B-33: Prism Specimen 3 Type 2 @ 28 Days After Failure

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

Figure B-34: Prism Specimen 4 Type 2 @ 28 Days After Failure

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

Figure B-35: Prism Specimen 1 Type 3 @ 28 Days After Failure

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

Figure B-36: Prism Specimen 2 Type 3 @ 28 Days After Failure

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

Figure B-37: Prism Specimen 3 Type 3 @ 28 Days After Failure

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

Figure B-38: Prism Specimen 4 Type 3 @ 28 Days After Failure

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

Figure B-39: Prism Specimen 1 Type 4 @ 28 Days After Failure

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

Figure B-40: Prism Specimen 2 Type 4 @ 28 Days After Failure

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

Figure B-41: Prism Specimen 3 Type 4 @ 28 Days After Failure

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

Figure B-42: Prism Specimen 4 Type 4 @ 28 Days After Failure

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

Figure B-43: Prism Specimen 1 Type 5 @ 28 Days After Failure

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

Figure B-44: Prism Specimen 2 Type 5 @ 28 Days After Failure

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

Figure B-45: Prism Specimen 3 Type 5 @ 28 Days After Failure

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

Figure B-46: Prism Specimen 4 Type 5 @ 28 Days After Failure

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

Figure B-47: Prism Specimen 1 Type 6 @ 28 Days After Failure

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

Figure B-48: Prism Specimen 2 Type 6 @ 28 Days After Failure

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

Figure B-49: Prism Specimen 3 Type 6 @ 28 Days After Failure

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

Figure B-50: Prism Specimen 4 Type 6 @ 28 Days After Failure

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

Figure B-51: Prism Specimen 1 Type 7 @ 28 Days After Failure

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

Figure B-52: Prism Specimen 2 Type 7 @ 28 Days After Failure

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

Figure B-53: Prism Specimen 3 Type 7 @ 28 Days After Failure

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

Figure B-54: Prism Specimen 4 Type 7 @ 28 Days After Failure

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

Figure B-55: Hollow Prism Specimen 1@ 42 Days After Failure

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

Figure B-56: Hollow Prism Specimen 2 @ 42 Days After Failure

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

Figure B-57: Hollow Prism Specimen 3 @ 42 Days After Failure

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

Figure B-58: Hollow Prism Specimen 4 @ 42 Days After Failure

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

Figure B-59: Prism Specimen 1 Type 1 @ 42 Days After Failure

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

Figure B-60: Prism Specimen 2 Type 1 @ 42 Days After Failure

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

Figure B-61: Prism Specimen 3 Type 1 @ 42 Days After Failure

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

Figure B-62: Prism Specimen 4 Type 1 @ 42 Days After Failure

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

Figure B-63: Prism Specimen 1 Type 2 @ 42 Days After Failure

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

Figure B-64: Prism Specimen 2 Type 2 @ 42 Days After Failure

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

Figure B-65: Prism Specimen 3 Type 2 @ 42 Days After Failure

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

Figure B-66: Prism Specimen 4 Type 2 @ 42 Days After Failure

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

Figure B-67: Prism Specimen 1 Type 3 @ 42 Days After Failure

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

Figure B-68: Prism Specimen 2 Type 3 @ 42 Days After Failure

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

Figure B-69: Prism Specimen 3 Type 3 @ 42 Days After Failure

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

Figure B-70: Prism Specimen 4 Type 3 @ 42 Days After Failure

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

Figure B-71: Prism Specimen 1 Type 4 @ 42 Days After Failure

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

Figure B-72: Prism Specimen 2 Type 4 @ 42 Days After Failure

Not Available

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

Figure B-73: Prism Specimen 3 Type 4 @ 42 Days After Failure

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

Figure B-74: Prism Specimen 4 Type 4 @ 42 Days After Failure

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

Figure B-75: Prism Specimen 1 Type 5 @ 42 Days After Failure

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

Figure B-76: Prism Specimen 2 Type 5 @ 42 Days After Failure

Not Available **Not Available**

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

Figure B-77: Prism Specimen 3 Type 5 @ 42 Days After Failure

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

Figure B-78: Prism Specimen 4 Type 5 @ 42 Days After Failure

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

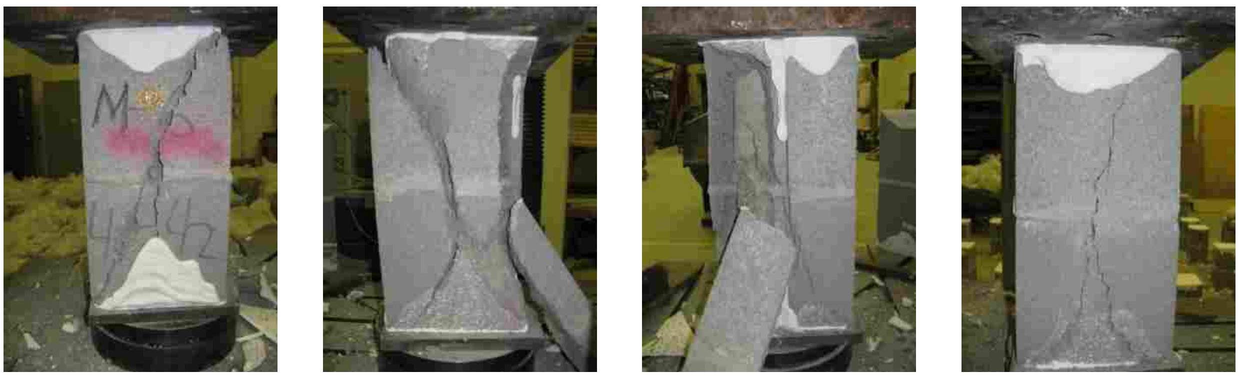
Figure B-79: Prism Specimen 1 Type 6 @ 42 Days After Failure

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

Figure B-80: Prism Specimen 2 Type 6 @ 42 Days After Failure

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

Figure B-81: Prism Specimen 3 Type 6 @ 42 Days After Failure



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

Figure B-82: Prism Specimen 4 Type 6 @ 42 Days After Failure

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

Figure B-83: Prism Specimen 1 Type 7 @ 42 Days After Failure

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

Figure B-84: Prism Specimen 2 Type 7 @ 42 Days After Failure

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

Figure B-85: Prism Specimen 3 Type 7 @ 42 Days After Failure

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

Figure B-86: Prism Specimen 4 Type 7 @ 42 Days After Failure

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

Figure B-87: Hollow Prism Specimen 1 @ 56 Days After Failure

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

Figure B-88: Hollow Prism Specimen 2 @ 56 Days After Failure

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

Figure B-89: Hollow Prism Specimen 3 @ 56 Days After Failure

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

Figure B-90: Hollow Prism Specimen 4 @ 56 Days After Failure

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

Figure B-91: Prism Specimen 1 Type 1 @ 56 Days After Failure

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

Figure B-92: Prism Specimen 2 Type 1 @ 56 Days After Failure

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

Figure B-93: Prism Specimen 3 Type 1 @ 56 Days After Failure

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

Figure B-94: Prism Specimen 4 Type 1 @ 56 Days After Failure

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

Figure B-95: Prism Specimen 1 Type 2 @ 56 Days After Failure

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

Figure B-96: Prism Specimen 2 Type 2 @ 56 Days After Failure

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

Figure B-97: Prism Specimen 3 Type 2 @ 56 Days After Failure

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

Figure B-98: Prism Specimen 4 Type 2 @ 56 Days After Failure

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

Figure B-99: Prism Specimen 1 Type 3 @ 56 Days After Failure

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

Figure B-100: Prism Specimen 2 Type 3 @ 56 Days After Failure

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

Figure B-101: Prism Specimen 3 Type 3 @ 56 Days After Failure

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

Figure B-102: Prism Specimen 4 Type 3 @ 56 Days After Failure

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

Figure B-103: Prism Specimen 1 Type 4 @ 56 Days After Failure

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

Figure B-104: Prism Specimen 2 Type 4 @ 56 Days After Failure

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

Figure B-105: Prism Specimen 3 Type 4 @ 56 Days After Failure

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

Figure B-106: Prism Specimen 4 Type 4 @ 56 Days After Failure

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

Figure B-107: Prism Specimen 1 Type 5 @ 56 Days After Failure

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

Figure B-108: Prism Specimen 2 Type 5 @ 56 Days After Failure

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

Figure B-109: Prism Specimen 3 Type 5 @ 56 Days After Failure

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

Figure B-110: Prism Specimen 4 Type 5 @ 56 Days After Failure

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

Figure B-111: Prism Specimen 1 Type 6 @ 56 Days After Failure

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

Figure B-112: Prism Specimen 2 Type 6 @ 56 Days After Failure

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

Figure B-113: Prism Specimen 3 Type 6 @ 56 Days After Failure

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

Figure B-114: Prism Specimen 4 Type 6 @ 56 Days After Failure

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

Figure B-115: Prism Specimen 1 Type 7 @ 56 Days After Failure

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

Figure B-116: Prism Specimen 2 Type 7 @ 56 Days After Failure

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

Figure B-117: Prism Specimen 3 Type 7 @ 56 Days After Failure

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

Figure B-118: Prism Specimen 4 Type 7 @ 56 Days After Failure

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

Figure B-119: Hollow Prism Specimen 1 @ 90 Days After Failure

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

Figure B-120: Hollow Prism Specimen 2 @ 90 Days After Failure

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

Figure B-121: Hollow Prism Specimen 3 @ 90 Days After Failure

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

Figure B-122: Hollow Prism Specimen 4 @ 90 Days After Failure

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

Figure B-123: Prism Specimen 1 Type 1 @ 90 Days After Failure

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

Figure B-124: Prism Specimen 2 Type 1 @ 90 Days After Failure

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

Figure B-125: Prism Specimen 3 Type 1 @ 90 Days After Failure

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

Figure B-126: Prism Specimen 4 Type 1 @ 90 Days After Failure

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

Figure B-127: Prism Specimen 1 Type 2 @ 90 Days After Failure

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

Figure B-128: Prism Specimen 2 Type 2 @ 90 Days After Failure

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

Figure B-129: Prism Specimen 3 Type 2 @ 90 Days After Failure

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

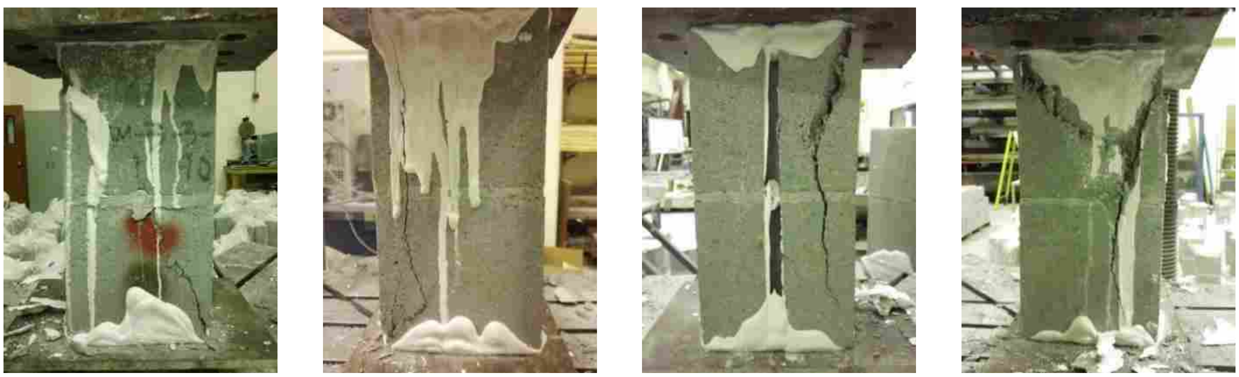
Figure B-130: Prism Specimen 4 Type 2 @ 90 Days After Failure

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

Figure B-131: Prism Specimen 1 Type 3 @ 90 Days After Failure

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

Figure B-132: Prism Specimen 2 Type 3 @ 90 Days After Failure



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

Figure B-133: Prism Specimen 3 Type 3 @ 90 Days After Failure

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

Figure B-134: Prism Specimen 4 Type 3 @ 90 Days After Failure

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

Figure B-135: Prism Specimen 1 Type 4 @ 90 Days After Failure

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

Figure B-136: Prism Specimen 2 Type 4 @ 90 Days After Failure

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

Figure B-137: Prism Specimen 3 Type 4 @ 90 Days After Failure

Not Available

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

Figure B-138: Prism Specimen 4 Type 4 @ 90 Days After Failure

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

Figure B-139: Prism Specimen 1 Type 5 @ 90 Days After Failure

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

Figure B-140: Prism Specimen 2 Type 5 @ 90 Days After Failure

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

Figure B-141: Prism Specimen 3 Type 5 @ 90 Days After Failure

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

Figure B-142: Prism Specimen 4 Type 5 @ 90 Days After Failure

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

Figure B-143: Prism Specimen 1 Type 6 @ 90 Days After Failure

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

Figure B-144: Prism Specimen 2 Type 6 @ 90 Days After Failure

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

Figure B-145: Prism Specimen 3 Type 6 @ 90 Days After Failure

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

Figure B-146: Prism Specimen 4 Type 6 @ 90 Days After Failure

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

Figure B-147: Prism Specimen 1 Type 7 @ 90 Days After Failure

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

Figure B-148: Prism Specimen 2 Type 7 @ 90 Days After Failure

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

Figure B-149: Prism Specimen 3 Type 7 @ 90 Days After Failure

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

Figure B-150: Prism Specimen 4 Type 7 @ 90 Days After Failure

Appendix C. Supplemental Material Data Sheets

LAFARGE CEMENT **Cement Test Report**

Mill Test Report Number:	SEA_NEWCEM_OCT10
YEAR:	2010
MONTH:	October
PLANT:	Seattle
CEMENT TYPE:	Grade 100 NewCem

Reference Cement

Fineness by Air Permeability (m^2/kg; ASTM C204)	395	
Fineness by 45 µm (No. 325) Sieve (% retain; ASTM C430)	3.9	
Compressive Strength (ASTM C109/C109 M)	psi	
7-day	4,760	
28-day (previous month's data)	5,550	
	Actual	Max Limit
Total Alkalies (Na_2O + 0.658 K_2O) (%, ASTM C114)	0.88	0.9

Slag

CHEMICAL ANALYSIS	Percent
Silica Dioxide (SiO_2, ASTM C114)	32.4
Ferric Oxide (Fe_2O_3, ASTM C114)	1.01
Aluminum Oxide (Al_2O_3; ASTM C114)	13.5
Calcium Oxide (CaO; ASTM C114)	43.9
Sulfur Trioxide (SO_3; ASTM C114)	4.8
Magnesium Oxide (MgO; ASTM C114)	4.0
Potassium Oxide (K_2O; ASTM C114)	0.36
Titanium Oxide (TiO_2, ASTM C114)	0.5
Loss on Ignition (L.O.I.; ASTM C114)	1.3

Slag

Fineness by Air Permeability (m^2/kg; ASTM C204)	507		
Fineness by 45 µm (No. 325) Sieve (% retain; ASTM C430)	1.9		
Compressive Strength (ASTM C109/C109 M)	psi	SAI	SAI Limit Min
7-day	4,340	91	75
28-day	6,340	114	95
Specific Gravity (Mg/m^3; ASTM C188)	2.89		
	Actual		Max Limit
Air Content of Mortar (%, ASTM C185)	7.1		12
Sulfide Sulfur (% S, ASTM C114)	0.7		2.5
Sulfate Ion (% as SO3, ASTM C114)	3.0		4

The ground granulated blast furnace slag complies with the current specification of the chemical physical requirement of ASTM C-989, AASHTO M-302 for grade 100 Ground Granulated Blast Furace Slag (GGBFS).

Certified by:

Daniel Waldron

Daniel Waldron
Quality Control Laboratory Supervisor
November 15, 2010

Figure C-1: Ground Granulated Blast Furnace Slag Manufacturer Data Sheet

HEADWATERS RESOURCES

Adding Value to Energy ™

ASTM C618 Testing of
Jim Bridger Fly Ash

Sample Type:	**3200-ton**	**Report Date:**	**5/13/2011**
Sample Date:	**3/17 - 3/21/11**	**MTRF ID**	**581JB**
Sample ID:	**BR-018-11-R**		

Chemical Analysis			**ASTM Limits Class F**	**ASTM Limits Class C**	**ASTM Test Method**
Silicon Dioxide (SiO2)	60.77	%			
Aluminum Oxide (Al2O3)	18.24	%			
Iron Oxide (Fe2O3)	4.27	%			
Sum of Constituents	83.28	%	70.0% min	50.0% min	D4326
Sulfur Trioxide (SO3)	0.68	%	5.0% max	5.0% max	D4326
Calcium Oxide (CaO)	5.46	%			D4326
Moisture	0.27	%	3.0% max	3.0% max	C311
Loss on Ignition	0.66	%	6.0% max	6.0% max	C311
Physical Analysis					
Fineness, % retained on #325	25.80	%	34% max	34% max	C311, C430
Strength Activity Index - 7 or 28 day requirement					C311, C109
7 day, % of control	92	%	75% min	75% min	
28 day, % of control	104	%	75% min	75% min	
Water Requirement, % control	96	%	105% max	105% max	
Autoclave Soundness	0.00	%	0.8% max	0.8% max	C311, C151
True Particle Density	2.34				

Headwaters Resources certifies that pursuant to current ASTM C618 protocol for testing, the test data listed herein was generated by applicable ASTM methods and meets the requirements of ASTM C618 for Class F fly ash.

Bobby Bergman
MTRF Manager

Materials Testing & Research Facility
2650 Old State Highway 113
Taylorsville, Georgia 30178
P: 770.684.0102
F: 770.684.6114
www.headwaters.com

Figure C-2: Class F Fly Ash Manufacturer Data Sheet

MASON MIX

PRODUCT NO. 1136

DIVISION 4

Masonry Mortaring
04 05 13

PRODUCT DESCRIPTION

QUIKRETE® Mason Mix is a contractor grade mortar mix designed for laying brick, concrete masonry units and stone.

PRODUCT USE

QUIKRETE® Mason Mix is a contractor grade mortar mix designed for laying brick, concrete masonry units and stone. QUIKRETE® Mason Mix is a pre-blended, sanded product. The standard formulation meets ASTM C 270 and C 1714 as Type S mortar. Other types are available by special request.

COLORS

QUIKRETE® Mason Mix is available in gray and additional colors by special order. Color can also be added to the product as it is mixed by adding QUIKRETE® Stucco and Mortar Color (#1319) to the mixing water. Twenty standard colors are available.

SIZES

- QUIKRETE® Mason Mix -
  - 60 lb (27.2 kg) bags
  - 80 lb (36.3 kg) bags

YIELD

- Each 80 lb (36.3 kg) bag of QUIKRETE® Mason Mix will lay up to 37 standard bricks or 13 standard (8" x 8" x 16" [200 mm x 200 mm x 400 mm]) blocks.

TECHNICAL DATA

APPLICABLE STANDARDS

ASTM International

- ASTM C 270 Specification for Mortar for Unit Masonry
- ASTM C 387 Specification for Packaged, Dry, Combined Materials for Mortar and Concrete
- ASTM C 1714 Specification for Preblended Dry Mortar Mix for Unit Masonry

PHYSICAL/CHEMICAL PROPERTIES

QUIKRETE® Mason Mix meets or exceeds the property requirements of ASTM C 270, ASTM C 387 and ASTM C 1714 for the type selected. Refer to Appendix XI of ASTM C270 for guidance in selecting the proper mortar type. See Table 1.

INSTALLATION

SURFACE PREPARATION

Surfaces to receive Mason Mix should be clean and free of dirt, loose debris, grease, oil, etc., for the best possible bond.

MIXING

- For each 80 lb (36.3 kg) bag, add 9 pt (4.3 L) of fresh water to mixer
- Turn the mixer on and begin adding bags of Mason Mix
- If the material becomes too difficult to mix, add additional water until a workable mix of trowelable consistency is obtained

Note - Final water content should be 9 - 14 pt (4.3 - 6.6 L) for each 80 lb (36.3 kg) bag and 7 - 10 pt (3.3 - 4.7 L) for each 60 lb (27.2 kg) bag.

INSTALLATION

- Apply a full bed of mortar onto the base, approximately 1/2" - 3/4" (12.7 - 19.1 mm) thick
- Push downward into the mortar bed and sideways against the previously laid block with a slight twisting motion
- Tool the mortar joints when they become thumbprint hard. This will make the mortar joint watertight and provide a neat appearance

Table 1

Hydraulic Cement- Lime Mortars or Cement Mortars			
Type	Minimum Compressive Strength, psi (MPa)	Water Retention Minimum %	Air content Maximum %
M	2500 (17.2)	75	12
S	1800 (12.4)	75	12
N	750 (5.2)	75	14[1]
O	350 (2.4)	75	14[1]
Masonry Cement Mortars			
Type	Minimum Compressive Strength, psi (MPa)	Water Retention Minimum %	Air content Maximum %
M	2500 (17.2)	75	18
S	1800 (12.4)	75	18
N	750 (5.2)	75	20[2]
O	350 (2.4)	75	20[2]

[1] When structural reinforcement is included, the maximum air content shall be 12%
[2] When structural reinforcement is included, the maximum air content shall be 18%

CURING

Curing of masonry mortars is required only if conditions are very hot, dry or windy. In such cases, a gentle mist of water applied to the

Figure C-3: Type M Mortar Manufacturer Data Sheet

GENEVA ROCK PRODUCTS, INC.

1565 West 400 North • P.O. Box 538 • Orem, UT 84059 • (801) 765-7800 • Fax (801) 765-7830 • www.genevarock.com

AGGREGATE SUBMITTAL

Report of Physical Properties

GRP Material Description: Washed, Concrete **Report Date:** March 22, 2011

GRP Material Code: SAND **Reviewed by:** Victor Johnson

Source Location/Code: Point of the Mountain / 525 **Report No.** 525SAND00111

TEST RESULTS				
Standard	**PHYSICAL PROPERTIES**		**Result**	
ASTM C 29 AASHTO T19	**Unit Weight**	Unit Weight, lbs./cu.ft. =	99.1	
		Voids, % =	38	
		Jigged / Loose / Rodded		
ASTM D1557 AASHTO T180	**Modified Proctor**	Max. density, lbs./cu.ft. =		
		Optimum Moisture, % =		
ASTM D698 AASHTO T99	**Standard Proctor**	Max. density, lbs./cu.ft. =		
		Optimum Moisture, % =		
ASTM D4318 AASHTO T89/90	**Liquid Limit**	Liquid Limit=	0	
	Plastic Limit	Plastic Limit=	0	
	Plasticity Index	Plasticity Index=	NP	
ASTM C131 AASHTO T96	**L.A. Abrasion**	Small Coarse Loss, % =		
		Grading/Revolutions, =		
ASTM C535	**L.A. Abrasion**	Large Coarse Loss, % =		
		Grading/Revolutions, =		
ASTM C 128 AASHTO T84	**Fine Specific Gravity & Absorption**	Bulk Specific Gravity (dry) =	2.569	
		Bulk Specific Gravity, SSD =	2.599	
		Apparent Specific Gravity =	2.649	
		Absorption, % =	1.17	
ASTM C 127 AASHTO T85	**Coarse Specific Gravity & Absorption**	Bulk Specific Gravity (dry) =		
		Bulk Specific Gravity, SSD =		
		Apparent Specific Gravity =		
		Absorption, % =		
ASTM D2419 AASHTO T176	**Sand Equivalent**	Sand Equivalent, % =	90	
ASTM C 88 AASHTO T104	**Soundness**	Coarse Soundness Loss, % =		
		Magnesium No. of Cycles =		
	Soundness	Fine Soundness Loss, % =	3	
		Sodium No. of Cycles =	5	
ASTM C 1252 AASHTO T304	**Fine Aggregate Angularity**	Uncompacted Voids, % =	46.9	
		Method C (as received material)		
ASTM C40 AASHTO T21	**Organic Impurities**	Coarse Aggregate, % =		
		Fine Aggregate, % =	Lighter Plate #1	
ASTM C142 AASHTO T112	**Clay / Friable Particles**	Coarse Aggregate, % =		
		Fine Aggregate, % =	0	
ASTM C123 AASHTO T113	**Lightweight Pieces**	Coarse Aggregate, % =		
		Fine Aggregate, % =	0	
ASTM D1883 AASHTO T193	**CBR**	Surcharge = 10 lbs CBR @ 0.1"=		
		Swell% = 0.0% CBR @ 0.2"=		
ASTM D5821	**Fractured Face**	1 or 2 Faces =		
		Fractured Face, % =		
ASTM D2487	**Soil Classification**	Group Symbol =		
		Group Name =		
ASTM D2488	**Soil Description & Identification**	Group Symbol =		
		Group Name =		

SIEVE ANALYSIS		
ASTM C136 AASHTO T27		
Sieve Size	**% Passing**	**Spec.**
450 mm (18")		
375 mm (15")		
300 mm (12")		
250 mm (10")		
225 mm (9")		
200 mm (8")		
150 mm (6")		
125 mm (5")		
100 mm (4")		
75.0 mm (3")		
63.0 mm (2-1/2")		
50.0 mm (2")		
37.5 mm (1-1/2")		
25.0 mm (1")		
19.0 mm (3/4")		
12.5 mm (1/2")		
9.5 mm (3/8")		
6.3 mm (1/4")		
4.75 mm (No.4)	100	
2.36 mm (No.8)	94	
2.00 mm (No.10)	85	
1.18 mm (No.16)	61	
0.600 mm (No.30)	37	
0.425 mm (No.40)	30	
0.300 mm (No.50)	20	
0.180 mm (No.80)		
0.150 mm (No.100)	6.4	
0.075 mm (No.200)	1.2	
ASTM D422		
Hydrometer =		
ASTM C566 AASHTO T255		
Moisture Content, % =		
ASTM C136 AASHTO T27		
Fineness Modulus (FM) =		
AASHTO M145		
Classification of Soils =		
ASTM D4791 Ratio =		
Flat & Elongated =		

GRP Materials Aggregate Physical Properties Report Version 02.11.08

Figure C-4: Fine Aggregate Manufacturer Data Sheet

GENEVA ROCK PRODUCTS, INC.

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AGGREGATE SUBMITTAL

Report of Physical Properties

GRP Material Description: Washed, Standard 3/8" x #16 **Report Date:** March 22, 2011

GRP Material Code: CHIP **Reviewed by:** Victor Johnson

Source Location/Code: Point of the Mountain / 525 **Report No.** 525CHIP00111

TEST RESULTS

Standard	Physical Properties		Result	Test Source
ASTM C 29 AASHTO T19	Unit Weight	Unit Weight, lbs./cu.ft. =	100	
		Voids, % =	37	
		Jigged Loose Rodded		
ASTM D1557 AASHTO T180	Modified Proctor	Max. density, lbs./cu.ft. =		
		Optimum Moisture, % =		
ASTM D698 AASHTO T99	Standard Proctor	Max. density, lbs./cu.ft. =		
		Optimum Moisture, % =		
ASTM D4318 AASHTO T89/90	Liquid Limit	Liquid Limit=		
	Plastic Limit	Plastic Limit=		
	Plasticity Index	Plasticity Index=		
ASTM C131 AASHTO T96	LA Abrasion	Small Coarse Loss, % =	24.7	
		Grading/Revolutions, =	D/500	
ASTM C535	LA Abrasion	Large Coarse Loss, % =		
		Grading/Revolutions, =		
ASTM C 128 AASHTO T84	Fine Specific Gravity & Absorption	Bulk Specific Gravity (dry) =		
		Bulk Specific Gravity, SSD =		
		Apparent Specific Gravity =		
		Absorption, % =		
ASTM C 127 AASHTO T85	Coarse Specific Gravity & Absorption	Bulk Specific Gravity (dry) =	2.597	
		Bulk Specific Gravity, SSD =	2.619	
		Apparent Specific Gravity =	2.654	
		Absorption, % =	0.8	
ASTM D2419 AASHTO T176	Sand Equivalent	Sand Equivalent, % =		
ASTM C 88 AASHTO T104	Soundness	Coarse Soundness Loss, % =	1.25	
		Sodium No. of Cycles =	5	
	Soundness	Fine Soundness Loss, % =		
		Magnesium No. of Cycles =		
ASTM C 1252 AASHTO T304	Fine Aggregate Angularity	Uncompacted Voids, % =		
		Method C (as received material)		
ASTM C40 AASHTO T21	Organic Impurities	Coarse Aggregate, % =		
		Fine Aggregate, % =		
ASTM C142 AASHTO T112	Clay / Friable Particles	Coarse Aggregate, % =	0	
		Fine Aggregate, % =		
ASTM C123 AASHTO T113	Lightweight Pieces	Coarse Aggregate, % =	0	
		Fine Aggregate, % =		
ASTM D1883 AASHTO T193	CBR	Surcharge = 10 lbs CBR @ 0.1"=		
		Swell% = 0.0% CBR @ 0.2"=		
ASTM D5821	Fractured Face	1 or 2 Faces =	1 = 100	
		Fractured Face, % =	2 = 95	
ASTM D2487	Soil Classification	Group Symbol =		
		Group Name =		
ASTM D2488	Soil Description & Identification	Group Symbol =		
		Group Name =		

SIEVE ANALYSIS

ASTM C136 AASHTO T27

Sieve Size	% Passing	Spec.
450 mm (18")		
375 mm (15")		
300 mm (12")		
250 mm (10")		
225 mm (9")		
200 mm (8")		
150 mm (6")		
125 mm (5")		
100 mm (4")		
75.0 mm (3")		
63.0 mm (2-1/2")		
50.0 mm (2")		
37.5 mm (1-1/2")		
25.0 mm (1")		
19.0 mm (3/4")		
12.5 mm (1/2")		
9.5 mm (3/8")	100	
6.3 mm (1/4")		
4.75 mm (No.4)	72	
2.36 mm (No.8)	24	
2.00 mm (No.10)		
1.18 mm (No.16)	5	
0.600 mm (No.30)		
0.425 mm (No.40)		
0.300 mm (No.50)	1.5	
0.180 mm (No.80)		
0.150 mm (No.100)		
0.075 mm (No.200)	1	
ASTM D422 Hydrometer =		
ASTM C566 AASHTO T255 Moisture Content, % =		
ASTM C136 AASHTO T27 Fineness Modulus (FM) =		
AASHTO M145 Classification of Soils =		
ASTM D4791 Ratio = Flat & Elongated =		

GRP Materials Aggregate Physical Properties Report Version 02.11.08

Figure C-5: Coarse Aggregate Manufacturer Data Sheet

April 25, 2011

CMT ENGINEERING

Amcor Masonry Products
333 South Redwood Road
North Salt Lake, Utah 84054

CMU Compression, Absorption, Moisture Content & Shrinkage

Project 0520 - Laboratory Services
Lab Number(s) 245709, 245710
Description 8x8x16" Regular CMUs, Production Date: 3/24/11

Absorption - Specimen Dimensions

Specimen I.D.	Dimensions			
	Length (in.)	Width (in.)	Height (in.)	Volume (cu. ft.)
A	15.61	7.70	7.62	0.53
B	15.65	7.68	7.69	0.53
C	15.70	7.69	7.56	0.53

Absorption - Specimen Mass Data

Specimen I.D.	Received		SSD		Immersed		Dry	
	Grams	Pounds	Grams	Pounds	Grams	Pounds	Grams	Pounds
A	14435.0	31.82	14891.6	32.83	7147.4	15.76	13744.3	30.30
B	14391.2	31.73	14909.0	32.87	7178.4	15.83	13735.3	30.28
C	14136.9	31.17	14725.6	32.46	7057.7	15.56	13460.7	29.68
Average	14321.0	31.57	14842.1	32.72	7127.8	15.71	13646.8	30.09

Absorption, Density, Net Area, Moisture Content

Specimen I.D.	Absorption		Dry Density (pcf)	Net Area (in^2)	Moisture Content (%)
	(pcf)	(%)			
A	9.24	8.35	110.75	61.62	60.20
B	9.47	8.55	110.87	61.62	55.88
C	10.29	9.40	109.54	61.62	53.46
Average	9.67	8.76	110.39	61.62	56.51

Compressive Strength

Specimen I.D.	Mass (lbs)	Gross Area (in^2)	Dimensions		Total Load (lbs)	Strength (psi)	
			Length	Width		Gross	Net
C1	31.52	120.20	15.61	7.70	245,980	2050	3990
C2	31.46	120.19	15.65	7.68	232,160	1930	3770
C3	31.47	120.73	15.70	7.69	264,130	2190	4290
Average	31.48					2060	4020

Shrinkage

Specimen I.D.	Shrinkage (%)
S1	NA
S2	
S3	
Average	

Manager

Figure C-6: Concrete Masonry Unit Manufacturer Data Sheet