PERFORMANCE OF NO VIBRATION/NO ADMIXTURE MASONRY GROUT CONTAINING HIGH REPLACEMENT OF PORTLAND CEMENT WITH FLY ASH AND GROUND GRANULATED BLAST FURNACE SLAG

A Thesis

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Architecture with a Specialization in Architectural Engineering

by

Eric Bateman

February 2014

COMMITTEE MEMBERSHIP

TITLE: Performance of No Vibration/No Admixture Masonry Grout Containing High Replacement of Portland Cement with Fly Ash and Ground Granulated Blast Furnace Slag

AUTHOR: Eric Bateman

DATE SUBMITTED: February 2014

COMMITTEE CHAIR: James Mwangi, Ph.D., S.E.
Professor of Architectural Engineering

COMMITTEE MEMBER: Craig Baltimore, Ph.D., S.E.
Professor of Architectural Engineering

ABSTRACT

Performance of No Vibration/No Admixture Masonry Grout Containing
High Replacement of Portland Cement with Fly Ash and Ground
Granulated Blast Furnace Slag

Eric Bateman

When hollow concrete masonry is used for construction in high seismic regions, structural designs typically require fully grouted walls. The grouting process is labor-intensive, time-consuming and has a high energy demand due to requirements of consolidation in each and subsequent grout lifts. Self-consolidating grout with admixtures has been successfully used without segregation in walls of up to 12.67 ft. in height. Investigation of self-consolidating grout mixes without admixtures has potential for sustainability improvement.

This thesis reports on the compression strength and consolidation observations of self-consolidating characteristics of no vibration/no admixture grout made by substituting various proportions of Portland cement with Type F fly ash and/or ground granulated blast furnace slag (GGBFS). The percentages of Portland cement replacement evaluated were 0%, 50%, 60%, and 70% for Type F fly ash. The percentages of Portland cement replacement evaluated were 0%, 60%, 70% and 80% for Type F fly ash and GGBFS.

Grout compressive strengths were evaluated from individually filled grout specimens constructed in concrete masonry hollow core units, dry cured, and tested after 7, 14, 28, 42, 56, and 130 days. Also, hollow concrete masonry walls were built 12.67 ft. tall and grouted. The relative performance was assessed by comparing to conventional grouted masonry and evaluating consolidation characteristics around mortar fins and reinforcement; compressive strength tests after 130 days of curing, and rebar pull-out tests were taken from various wall heights.

All experimental grouts had acceptable consolidation characteristics but fly ash replacement grouts did not meet the compressive strength requirements.

Keywords: Self-Consolidating Grout, Fly Ash Replacement, No Vibration/Admixture

ACKNOWLEDGMENTS

The following organizations have supported this study and without their monetary, material, and labor contributions, this test program would not have been possible: Concrete Masonry Association of California and Nevada (CMACN), Masonry Institute of America (MIA), Pacific Coast Building Products, Basalite Concrete Products, Bricklayers & Allied Craftworkers Local Union No. 4, and Coastal Demo Inc.

I would also like to thank Ray Ward, the College of Architecture and Design Laboratory Technician, for his assistance in the Laboratories.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOMENCLATURE

A_s = effective cross-sectional area of reinforcement, in.^{2}
d_1 = largest diameter of circular spread of grout, in.
d_2 = diameter perpendicular to d_1, in.
d_b = nominal diameter of reinforcement, in.
f_g = compressive strength of grout, psi
f'_m = specified compressive strength of masonry after 28 days of curing, psi
f_s = calculated stress in reinforcement at service loads, psi
f_y = specified yield strength of steel for reinforcement, psi
K = dimension used to calculate reinforcement development, in.
l = embedment length of reinforcement, in.
l_d = development length of straight reinforcement, in.
T = tensile axial force in the reinforcement, lb.
τ = bond strength between reinforcement and concrete or grout, psi
γ = reinforcement size factor

1.0 INTRODUCTION

The purpose of this thesis is to investigate whether high Type F fly ash and/or Ground Granulated Blast Furnace Slag (GGBFS) replacement of Portland cement in grout, without the use of admixtures and mechanical consolidation, can function as self-consolidating grout. Self-consolidating grout with fly ash and/or GGBFS replacement can provide higher sustainability in masonry construction and also has important economic benefits. The replacement of cement with fly ash and/or GGBFS has the ability to promote sustainability, which is meeting present needs without compromising the ability of future generations to meet their needs. Partially replacing cement needed in grout with recycled material would lessen the demand for cement and in turn cement production. Lowering cement production would decrease the amount of fossil fuels and raw materials used for production and the by-products, such as carbon dioxide.

Grout, like concrete, is a cementitious material, typically used in hollow concrete masonry construction. In high seismic regions, structural designs require fully grouted walls. A fully grouted 8x8x16 in. concrete masonry unit (CMU) contains approximately 52 percent grout based on the total volume. Since large amounts of grout are required, a more sustainable grout mixture would benefit the environment by reducing cement use. In addition, the reduction of cement use would increase the flowability of the grout mixture, potentially allowing the grout to become self-consolidating without the addition of an admixture.

A self-consolidating grout mixture must:

- be fluid enough to flow and fill the forms under its own weight without any addition of external energy (i.e., vibration);

- remain homogeneous regardless of the distance it flows or the height of vertical discharge (i.e., no segregation of aggregates);

- flow through congested reinforcement and other confined spaces without losing its filling ability characteristics (Bonen and Shah 2005).

Self-consolidating grout in concrete masonry construction also has important economic benefits. Conventional grouting is labor-intensive and time-consuming due to the number of lifts required and use of a mechanical vibrator. Each grout lift needs to be vibrated before the next lift is placed to ensure proper consolidation, which is a time-consuming process and can be a difficult task to perform in high reinforcement regions. Self-consolidating grout allows for proper consolidation without the use of a mechanical vibrator, saving time and money.

2.0 BACKGROUND

Masonry grouts with high fly ash and/or GGBFS replacement of Portland cement have environmental benefits (2.1) and economic benefits (2.2). In order for the masonry grouts to function as self-consolidating grouts, the masonry grouts must meet the requirements of self-consolidating grout (2.3).

2.1 Environmental Benefits

Partially substituting fly ash and/or GGBFS for Portland cement in grout can help to reduce the cement industry's carbon footprint. Carbon footprint is the total amount of greenhouse gas emissions, including carbon dioxide, caused by an organization, person, or product. The primary sources of anthropogenic (produced by humans) carbon dioxide emissions are the combustion of fossil fuels, deforestation (and the associated reduction in carbon sequestration), unsustainable combustion of biomass, and the emission of mineral sources of carbon dioxide (Worrell et al. 2001). In the manufacturing process for cement, more than one fifth tonne of carbon dioxide is emitted for every tonne of cement produced. Sixty percent of the carbon dioxide emissions from cement production are due to the chemical process known as calcination, in which carbon dioxide is liberated from the decomposition of raw materials (mostly limestone) in a high temperature cement kiln (Mwangi and Baltimore 2009). The remaining 40% of the carbon dioxide emissions are due to the combustion of fossil fuels (typically coal or petroleum coke) in the kiln. Currently, there are no viable remedies to reduce the carbon dioxide emission due to

calcination, and measures to reduce the carbon dioxide emissions due to combustion (e.g., fuel substitution and energy efficiency improvements) are typically very costly.

In 1995, global cement production was estimated to be 1453 million metric tons and China led the way with the most cement production in the world, growing at 12.2 percent annually. Because of the importance of cement as a construction material and the geographic abundance of the main raw materials, cement is produced in virtually all countries. The cement industry contributes about 5 percent to global anthropogenic carbon dioxide emissions (Worrell et al. 2001). To help solve the emission problems, in 2006, California put into law (California Global Warming Solutions Act of 2006) a regulatory program to reduce carbon dioxide emissions to the 1990 levels, by the year 2020 (Mwangi and Baltimore 2009).

The long term goal should be to find a way to reduce the carbon dioxide emissions from each tonne of concrete produced. Many researchers have attempted to reduce the carbon dioxide emissions from the chemical process but there have not been viable solutions (Huntzinger et al. 2009). Therefore, the short time goal should be to reduce the amount of cement used in concrete and grout. Reducing the amount of cement in grout alone would not be appropriate because the strength of the grout would decrease and become inadequate. A partial substitute for the cement that would provide additional strength benefits would be needed. Currently, fly ash is used to replace Portland cement, more commonly, in low amounts of approximately 15 to 25 percent by weight, and GGBFS replaces cement at approximately 15 to 40 percent by weight. Fly ash and

GGBFS replacements of Portland cement have already been recognized by the U.S. Green Building Council (USGBC) as a sustainable solution to help reduce the cement industry's carbon footprint. USGBC has developed the Leadership in Energy and Environmental Design (LEED) rating system which is a voluntary, consensus-based nation standard for developing high performance sustainable buildings. In order for a building to become a LEED certified project, a minimum of 40 points on a 110-point LEED rating system scale is needed for commercial buildings and 45 points on a 136-point scale for homes. Fly ash and/or GGBFS replacement of Portland cement can contribute to points to reach this certification. In California there are many municipalities who require LEED certification on their newly constructed buildings (Kang and Kren 2007).

Fly ash is a fine-grained industrial waste particulate that comes from the combustion of coal. Fly ash can cause severe environmental problems if not disposed of correctly. The utilization of fly ash in concrete and grout instead of dumping the waste material in landfills is a solution to properly dispose of this material in a sustainable way. There are two types of fly ash that are defined by ASTM C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete; Type C and Type F. Type F fly ash is more commonly used, so this thesis will focus on the use of Type F fly ash. Fly ash, a pozzolan, creates a pozzolanic reaction when combined with calcium hydroxide in the presence of water to form cementitious properties. Fly ash has

a slower development of strength than that of cement and acts as a plasticizer, improving the workability of the grout mixture.

Blast furnace slag is a by-product of iron and steel production. Granulated blast furnace slag is formed when molten blast furnace slag is quenched in water, and GGBFS is formed by subsequent grinding, reducing the particle size to the same fineness of cement. There are three types of GGBFS that are defined by ASTM C 989 Standard Specification for Slag Cement for Use in Concrete and Mortars; Grade 120, Grade 100, and Grade 80. This thesis will focus on Grade 100. GGBFS hydrates like Portland cement, but has a slower development of strength than that of cement and improves the workability of the grout mixture.

2.2 Economic Benefits

In high seismic zones, structural designs require fully grouted walls for hollow concrete masonry. Hollow concrete masonry walls typically have close spacing of reinforcement due to high seismic demands. Grout is required to flow into all areas of the highly reinforced masonry wall to bind the reinforcement and masonry units together. For conventional grout, a mechanical vibrator is required for consolidation to eliminate air voids and to help ensure sufficient bond strength between materials. The vibrator may be difficult to get into small spaces because of the closely spaced reinforcement (Khayat 1999). Another feature of conventional grouting is pouring the grout at different heights or lifts: low lift and high lift. A low lift is approximately 4 ft. high and a high lift is approximately 12 ft. high. Grouting a low lift normally contains less error of

consolidation (fewer voids) than a high lift when using a mechanical vibrator, but it takes several low lifts to reach the height of the high lift. Each lift must be consolidated before the next lift is placed, which takes more time. For high lifts, consolidation is harder to achieve, so the labor requires a more skilled worker. The processes of vibrating multiple lifts are labor-intensive and time-consuming which increases costs.

A self-consolidating grout would cut costs by allowing the grout to be poured from high lifts assuming it properly consolidates under its own weight without the use of a mechanical vibrator. Self-consolidating grouts, with the use of admixtures, already exist and are available commercially (Ryan and Farnsworth 2003). Admixtures in self-consolidating grout are primarily used to increase the workability of the grout mixture so that less water is required (thereby increasing the strength of the grout). Admixtures are also used for various effects, including, controlled setting and hardening, improved strength, and better durability. Although admixtures commonly benefit a grout mixture, they can occasionally cause incompatibility problems due to their interaction with cement or other admixtures, can result in application errors in the field, and are relatively expensive (Rixom and Mailvaganam 1999). High replacement of Portland cement with fly ash and/or GGBFS may increase the grout's workability so that admixtures are not needed.

2.3 Requirements of Self-Consolidating Grout

According to ASTM C 476 Standard Specification for Grout for Masonry; a grout may qualify as a self-consolidating grout, the grout mixture needs to provide a slump

flow of 24 to 30 inches (determined by ASTM C 1611 Standard Test Method for Slump Flow of Self-Consolidating Concrete), a Visual Stability Index (VSI) of not greater than one (determined by Appendix XI of ASTM C 1611), and a minimum compressive strength of 2000 psi after 28 days of curing (in accordance with ASTM C 1019 Standard Test Method for Sampling and Testing Grout). The slump flow test and VSI help to assure that the self-consolidating grout is fluid enough to flow under its own weight without vibration while remaining homogeneous. In addition, a self-consolidating grout must be able to flow through congested reinforcement while still fulfilling the strength requirements of conventional grout.

2.3.1 Compressive Strength

Initial research, Phase 1 (Mwangi and Baltimore 2009) and Phase 2 and 3 (Bradfield 2011), investigated the development of compressive strengths of grouts with partial Portland cement replacement with Type F fly ash, and combinations of Type F fly ash and GGBFS Grade 100. The compressive strengths were compared with the minimum compressive strength of 2000 psi after 28 days of curing prescribed by building code (IBC 2009) and ASTM C 476. The results of the testing indicated that partial fly ash and/or GGBFS replacement grout is a viable alternative to traditional grout. Phase 1 testing (Mwangi and Baltimore 2009), fly ash replacement of cement, included 180 specimens that were formed in the cells of hollow CMU, cured in both wet and dry conditions, and sawn cut to 4x4x8 inches (nominal) . The cured specimens were tested after 7, 14, 28, 42, and 56 days. The percentages of Portland cement replaced were

0%, 20%, 30%, 40%, 50%, and 60%. The specimens were prepared and tested in conformance to ASTM C 1019. The results of the testing showed that grouts with 20% and 30% replacement (by weight) could be treated as traditional grout. Grout with 40% and 50% replacement (by weight) requires a longer curing period to reach compressive strengths. The 60% grout replacement did not appear to meet strength standards. The longer cure period is characteristic of the pozzolanic nature of fly ash solidification. Thus in Phase 2 (Bradfield 2011), compression tests were again performed for similar specimens with fly ash replacement of cement, however longer cure periods were investigated. In Phase 2, 180 specimens were tested after 7, 14, 28, 42, 56 and 180 days. The percentages of Portland cement replaced were 0%, 20%, 30%, 40%, 50%, and 60%. The specimens were prepared and tested in conformance to ASTM C1019. The results of Phase 2 testing confirmed, from Phase 1, that grouts with 20% and 30% replacement (by weight) could be treated as traditional grout. Grout with 40% and 50% replacement (by weight) required a longer curing period (42 days) to reach the required 28 day compressive strengths. The 60% grout replacement required 56 days to meet minimum strengths and 180 days to exceed these strengths. The Phase 3 testing (Bradfield 2011) included both fly ash and GGBFS for the replacement of Portland cement. Testing was after 7, 14, 28, 42, 56 and 180 days. The percentages of Portland cement replaced were 50%, 60%, 70% and 80%. The amount of fly ash replacement was kept constant at 25% and the amount of GGBFS was varied to meet the total replacement percentage. The results showed that all percentages of Portland cement replacement required a 42 day

cure time to reach compressive strengths. This research demonstrated that fly ash and/or GGBFS replacement of Portland cement could satisfy the compressive strength requirements of ASTM C 476 with a longer duration of curing time.

2.3.2 Consolidation Characteristics

Research by the National Concrete Masonry Association (NCMA) confirmed proper consolidation from self-consolidating grout that contained admixtures (Greenwald et al. 2006). The research documented the behavior using visual assessment throughout the height of 12.67 ft. masonry wall assemblies. Three sample walls, 12.67 ft. high, were constructed with separate vertically aligned grout columns intended to evaluate the influence of mechanical consolidation and placement of horizontal reinforcement. The grouts, which came from a local supplier, were pumped in one 12.67 ft. high lift. The conventional grout used a mechanical vibrator to consolidate the grout, while the self-consolidating grout did not. After 14 days of curing the walls were cut into sections at various wall heights and the grouts were visually inspected for the presence of any segregation and air voids, particularly under the horizontal reinforcement and mortar fins. Specific conclusions were (1) all specimens indicated no visible segregation; and (2) all specimens exhibited complete grout fill under and around reinforcement and mortar fins. This research demonstrated that self-consolidating grout could achieve the same quality of consolidation as conventional grout.

2.3.3 Bond Strength

Stress design of reinforced masonry uses the grout, CMU, and mortar together to resist the compression forces, while steel reinforcement resists the tension forces. For designed tension forces to be resisted by the reinforcement there must be a transfer of forces, or bond, between the grout and reinforcement. Rebar pullout tests, as shown in Figure A, determine the stress in reinforcement, f_s, at a service load, T, caused by the bond.

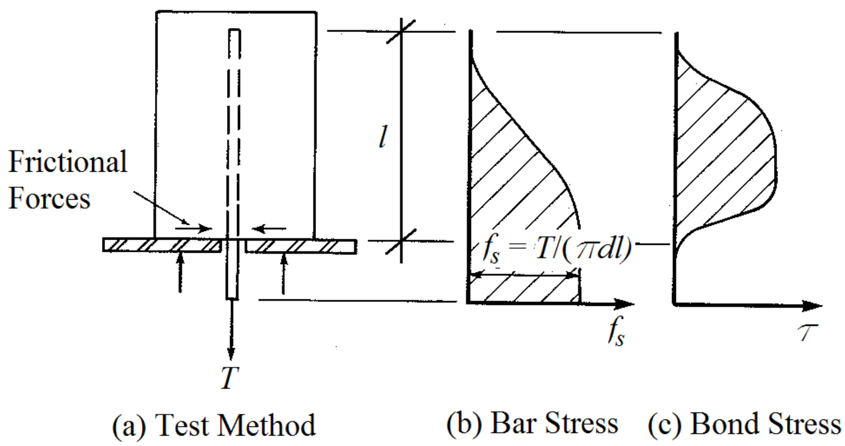


Figure A: Rebar Pullout Test
Source: Modified from Wight and MacGregor 2009

The bond strength, τ, is equal to the calculated stress in reinforcement, f_s. From the rebar pullout test, the ultimate axial load, T, can used to determine the bond strength between the grout and reinforcement, given in the equation

$$\tau = \frac{T}{\pi d_b l} \quad , \qquad \text{Eq.1}$$

Where
τ is the bond strength (psi),
T is the tensile axial force in the reinforcement (lb.),
d_b is the nominal diameter of reinforcement (in.), and
l is the embedment length (in.).

According to the provisions of ACI 318, the embedment length of reinforcement for sufficient anchorage is inversely proportioned to the square root of the compressive strength, implying that the bond strength should be linearly proportional to the square root of compressive strength (Foroughi, Dilmaghani, and Famili 2008), as shown in the equation

$$\tau = 12.043\sqrt{f_g} \quad , \qquad \text{Eq.2}$$

Where
τ is the bond strength (psi), and
f_g is the compressive strength of grout (psi).

Equation 2 is applicable for conventional grouts, while a self-consolidating grout may not have the same relationship between the compressive strength and bond strength. By preforming separate tests, compression and rebar pullout, the relationship between the compressive strength and bond strength can help determine the validity of Equation 2 applied to self-consolidating grouts.

Research using self-consolidating concrete has confirmed that adequate bond strength could be achieved and had similar characteristics to that of conventional concrete (Foroughi, Dilmaghani, and Famili 2008). The research investigated the bond between self-consolidating concrete and steel reinforcement by conducting rebar pullout tests from cubic specimens. The self-consolidating concrete was compared to conventional concrete that was mechanically vibrated. The results showed (1) that the self-consolidating concrete specimens generated a higher bond to the reinforcement than conventional concrete; and (2) the correlation between bond strength and compressive strength of conventional concrete was more consistent.

The design of reinforced masonry structures requires that the reinforcement must be anchored so as to fully develop the reinforcing bar to its yield stress. For full development to be achieved, a minimum development length, l_d, of the reinforcing bar must be provided through anchorage to the grout. The code (Masonry Building Code 2008) defines a minimum development length for reinforcement embedded in grout, shown in the equation

$$l_d = \frac{0.13 d_b^2 f_y \gamma}{K\sqrt{f'_m}} \quad , \qquad \text{Eq.3}$$

Where
- l_d is the development length of straight reinforcement (in.),
- d_b is the nominal diameter of reinforcement (in.),
- f_y is the specified yield strength of steel for reinforcement (psi),
- γ is the reinforcement size factor (dimensionless),
- K is the dimension used to calculate reinforcement development (in.), and
- f'_m is the specified compressive strength of masonry after 28 days of curing (psi).

3.0 LITERATURE REVIEW

There has been many research papers related to this thesis that have provided similar conclusions to each other. The previous research papers described in the background and the following literature review section provides enough evidence to validate the value for this thesis.

The report “Evaluation of Self-Consolidating Concrete for Bridge Structure Applications” evaluated self-consolidating concrete for the homogeneity of the mix (Horta 2005). The purpose was to compare the consolidation properties of different self-consolidating concrete mixtures; half of the mixtures were consolidated with a vibrator and the other half were not. Each self-consolidating concrete mixture was poured into wall panel formwork with vertical and horizontal reinforcement. After curing, the self-consolidating concrete was evaluated on (1) surface finish, (2) compressive strength, and (3) aggregate distribution from cut specimens. (1) From visual inspection of the surface finish, the diameter of air voids greater than or equal to 1/8 in. were recorded. The results showed that the self-consolidating concrete without vibration experienced more air voids than the self-consolidating concrete with vibration. (2) Concrete compression tests evaluated the compressive strength of three inch diameter cores from the top, middle, and bottom of the walls. There were no significant differences in compressive strength between the self-consolidating grouts that were vibrated and those that were not vibrated. (3) The walls were cut vertically into thirds and through visual inspection there were no segregations of aggregates in any mixture and were no significant differences of air voids

between the self-consolidating concrete with and without mechanical vibration.

The report "Evaluating the Static Segregation Resistance of Hardened Self-Consolidating Concrete using Image Processing Technology" compared the segregation of aggregates from cut sections of cured self-consolidating concrete through the Hardened Visual Stability Index and an image processing technology (Fang and Labi 2006). The Hardened Visual Stability Index is a varying visual rating scale of aggregate segregation on a scale of 0 to 4: 0 (stable), 1 (stable with slight variance in size), 2 (unstable), and 3 (unstable and clearly segregated aggregates). The image processing technology used a binary image of light colors and complex algorithms to evaluate a sample in terms of the Hardened Visual Stability Index. The findings concluded that the image processing technology was accurate for the report, but further field tests are needed to completely validate the reliability of the algorithms. Also, the Hardened Visual Stability Index may face errors in human judgment, subjectivity of ratings, and low efficiency.

The report "The Feasibility of Using Self-Consolidating Concrete (SCC) in Drilled Shaft Applications" compared conventional drilled shaft concrete and self-consolidating concrete in a drilled shaft application (Hodgson et al. 2004). Drilled shafts were created with congested reinforcement and filled with either conventional drilled shaft concrete or self-consolidating concrete. The piles were exhumed and cross sections were cut to visually observe the segregation of aggregates and the presence of air voids near the reinforcement. The study concluded that the self-consolidating concrete and

conventional drilled shaft concrete mixtures showed no significant signs of aggregate segregation throughout the cross sections. The self-consolidating concrete contained air voids from 1/16 to 1/8 inches in diameter.

4.0 EXPERIMENT

Two experiments were conducted to investigate if high Portland cement replacement grout could be characterized as self-consolidating grout. The experimental grout mixtures used fly ash, or fly ash and GGBFS in combination, as the replacements for Portland cement. No admixtures were added to any of the grout mixtures. The experimental grouts were compared to a baseline grout mixture (conventional grout: mechanical consolidation and no Portland cement replacement). The same grout mixtures were used for both experiments so that they could be linked to each other.

The first experiment, The Compression Experiment, investigated the performance of the potential self-consolidating grouts through compressive strengths of individually grouted CMU at various curing times. The second experiment, The Wall Experiment, investigated the behavior and performance of the potential self-consolidating grouts (experimental grouts) throughout the height of a high lift wall assembly through visual assessment and physical evaluation. Specifically, the research focused on three different aspects of consolidation by comparing the potential self-consolidating grouts to conventional grouted masonry: a visual inspection of the flow characteristics around the mortar fins and reinforcement in the CMU cells, an evaluation of compressive strengths after 130 days of curing, and an evaluation of the bond between the reinforcements and grouts (rebar pullout tests).

All tests were conducted at the High Bay Laboratory and Concrete Laboratory in the Architectural Engineering department of the College of Architecture and

Environmental Design at the California Polytechnic State University in San Luis Obispo, California.

4.1 Materials

Materials used in the investigation were:

- Portland cement Type II & V complying with ASTM C 150
- Coal fly ash Type F complying to ASTM C 618
- Ground granulated blast furnace slag (GGBFS) Grade 100 complying with ASTM C 989
- Type S masonry mortar complying with ASTM C 270
- Hollow concrete masonry units (CMUs) complying with ASTM C 90
- Coarse aggregate (3/8 in.) pea gravel complying with ASTM C 404
- Fine aggregate washed concrete sand complying with ASTM C 404
- #3 and #5 Deformed Rebar complying with ASTM A 615
- Potable water

4.2 Grout Mixture Proportions

The grout mixture proportions including fine aggregate, coarse aggregate (3/8 in. pea gravel), total cementitious material, and water remained constant for all of the grout mixtures. The grout proportions, by volume, followed the upper bound on aggregates from Table 1 of ASTM C 476 and can be seen in Table 1.

Table 1: Grout Proportions by Volume, Following Table 1 of ASTM C 476

Grout Proportions by Volume				
Type	Parts by Volume of Cementitious Material	Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition	
			Fine	Coarse
Coarse Grout, (max 3/8 in. agg.)	1	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials

The only factor in the grout proportions that changed between each mixture was within the cementitious materials. There were three types of cementitious material tested: no-replacement of Portland cement, Type F fly ash replacement of Portland cement, and Type F fly ash and GGBFS Grade 100 replacement of Portland cement. The no-replacement grout, referred to as conventional grout or the "base mix design", represents the grout commonly used in industry and which requires vibration for consolidation.

There were three grout mixtures within both the fly ash replacements (50F, 60F, and 70F), and fly ash and GGBFS replacements (60SF, 70SF, and 80SF), known as the experimental grouts. The proportions for cementitious material for the fly ash and/or GGBFS replacement used are shown in Table 2.

Table 2: Proportions of Fly Ash and GGBFS Replacement of Portland Cement

Type F Fly Ash and GGBFS Replacements			
Test Name	Cementitious Material		
	Cement (% Vol.)	Fly Ash (% Vol.)	GGBFS (% Vol.)
50F	50	50	0
60F	40	60	0
70F	30	70	0
60SF	40	15	45
70SF	30	17.5	52.5
80SF	20	20	60
100C	100	0	0

ASTM C 476 specifies that the proportion of water required for a conventional grout must provide a slump of 8 to 11 inches, as determined by ASTM C 143 Standard Test Method for Slump of Hydraulic-Cement Concrete. The "base mix design" was determined to have a water-to-cement ratio of 1.375 by volume, which provided an average slump of 9.75 inches, as determined following ASTM C 143. The water-to-cementitious materials ratio was kept constant at 1.375 by volume for all of the grout mixtures.

According to ASTM C 476, in order for the experimental grouts to qualify as self-consolidating, the grout mixtures needed to provide a slump flow of 24 to 30 inches (determined by ASTM C 1611), a Visual Stability Index (VSI) of not greater than 1 (determined by Appendix XI of ASTM C 1611), and a minimum compressive strength of

2000 psi after 28 days of curing (in accordance with ASTM C 1019).

4.3 The Compression Experiment

Seven grout mixtures were tested: conventional grout, 50%, 60%, and 70% fly ash replacement of cement, and 60%, 70%, and 80% fly ash and GGBFS replacement of cement, as shown in Table 2. The grout samples were dry cured within the cells of 8x8x16 in. CMUs. Three grout specimens per mixture were tested after 7, 14, 28, 42, 56, and 130 days of curing, as shown in Table 3. Altogether, a total of 126 specimens were tested for The Compression Experiment.

Table 3: Number of Grout Test Specimens for Each Curing Process

Number of Grout Test Specimens for Each Curing Process									
Test Name	Cementitious Material			Test Age (Days)					
				7	14	28	42	56	130
	Cement (% Vol.)	Fly Ash (% Vol.)	GGBFS (% Vol.)	Number of Specimens					
100C	100	0	0	3	3	3	3	3	3
50F	50	50	0	3	3	3	3	3	3
60F	40	60	0	3	3	3	3	3	3
70F	30	70	0	3	3	3	3	3	3
60SF	40	15	45	3	3	3	3	3	3
70SF	30	17.5	52.5	3	3	3	3	3	3
80SF	20	20	60	3	3	3	3	3	3
Total Number of Specimens = 126									

Seven grout batches were prepared, one for each of the grout mixtures listed in Table 3. The material proportions were batched by volume into five gallon buckets and mixed in a mechanical mixer in accordance with ASTM C 476 as seen in Figure B. Each mix was batched only one time and a slump test, following ASTM C 143, was provided

for the conventional grout or a slump flow test, following ASTM C 1611, was provided for the experimental grouts (shown in Appendix A).

Figure B: Grout Materials Mixing in Mechanical Mixer
Source: Author Photo

Grout specimens were made in accordance with ASTM C 1019, with one exception: the grouts were poured into the cores of 8x8x16 in. CMUs to form the specimens, as seen in Figure C(1), rather than constructing a grout mold using four CMUs. This exception was made in order to save space and mimic the same water absorption the grout experiences while curing in the core of the CMU, yet still providing the absorptive mold requirement in ASTM C 1019. The grouted CMUs were dry cured, complying with ASTM C 157 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, as shown in Figure C(2).

Figure C: (1) Placing Grout in Cores of CMUs and (2) Dry Curing Grout Specimens
Source: Author Photos

One day prior to testing, the compression test specimens were made by saw cutting the grout specimens to 4x4x8 in. (nominal) by using a 20 in. diameter diamond blade wet saw, satisfying the dimensional requirements of ASTM C 1019 as shown in Figure D.

Figure D: (1) Wet Saw Cutting Specimens and (2) Final Grout Compression Specimens
Source: Author Photos

After cutting, the samples were returned to their curing environment until testing. The specimens were capped in accordance to ASTM C 1552 Standard Practice for Capping Concrete Masonry Units, Related Units and Masonry Prisms for Compression Testing, and tested in compression in accordance with ASTM C 1019 as shown in Figure E.

Figure E: (1) Capping of Grout Compression Specimens and (2) Compression Testing
Source: Author Photos

4.4 The Wall Experiment

4.4.1 Wall Design

Four walls were constructed by professional masons in one lift for the Wall Experiment. All of the walls were built with a running bond using double square core, single wythe 8x8x16 in. CMU, and 19 courses high for a total height of 12.67 ft., as seen in Figure F(1). Full mortar bedding was used to prevent the grout from flowing into adjacent grout columns. Cleanouts were provided in the first course of all the columns to be grouted as shown in Figure F(2).

Figure F: (1) Wall Elevation and (2) Location of Cleanouts
Source: Author Photos

The walls were labeled 1, 2, 3, and 4. Walls 1, 2, and 3 were used for the evaluation of compression strengths and visual inspection of the flow characteristics around the mortar fins and reinforcement of the grouts at varying heights along the wall. Wall 4 was used for the evaluation of the bond between the reinforcements and grouts at varying heights along the wall.

Walls 1, 2, and 3 were 4.0 feet wide, and consisted of six grout columns. The walls had two No. 5 horizontal reinforcement bars placed at bond beam CMUs at 2.0 feet on center vertically, as shown in Figure G(1). The bond beams were constructed on-site by cutting and chipping away typical CMUs as seen in Figure G(2).

Figure G: (1) Horizontal Steel Placement and (2) Constructed Bond Beams
Source: Author Photos

The two No.5 reinforcement bars at each reinforcement layer were spaced equally, resulting in three spaces approximately 1 ¼ in. wide, as shown in Figure H.

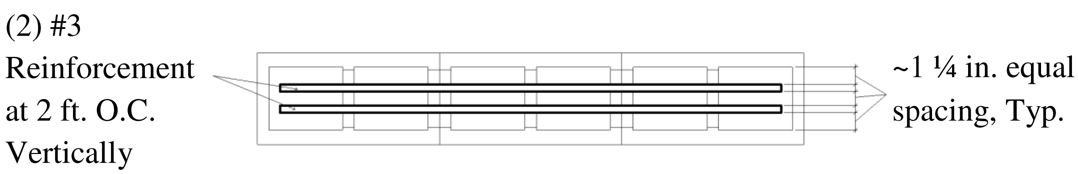


Figure H: Plan View of Horizontal Reinforcement on Bond Beams
Source: Author Diagram

Wall 4 was 5.33 ft. wide, and consisted of eight grout columns. The wall had one No. 3 vertical reinforcing bar placed as close to the middle of each grout column as possible, throughout the entire height of the column, as shown in Figure I.

Figure I: Vertical Steel Placement
Source: Author Photo

Figures J(1) and J(2) illustrate each wall, indicating corresponding grout type, reinforcement locations, and mechanical consolidation. Fly ash replacement grouts were used in wall 1, fly ash and GGBFS replacement grouts used in wall 2, conventional grout used in wall 3, and all grouts used in wall 4. For walls 1 and 2, each mixture of grout was used in two grout columns. For wall 3, three grout columns were vibrated and two were not. The first grout column in wall 3 (Column ID: 3-1-1) was not properly mechanically vibrated, so that column was ignored in the experiment. For wall 4, each mixture of grout was used in one grout column.

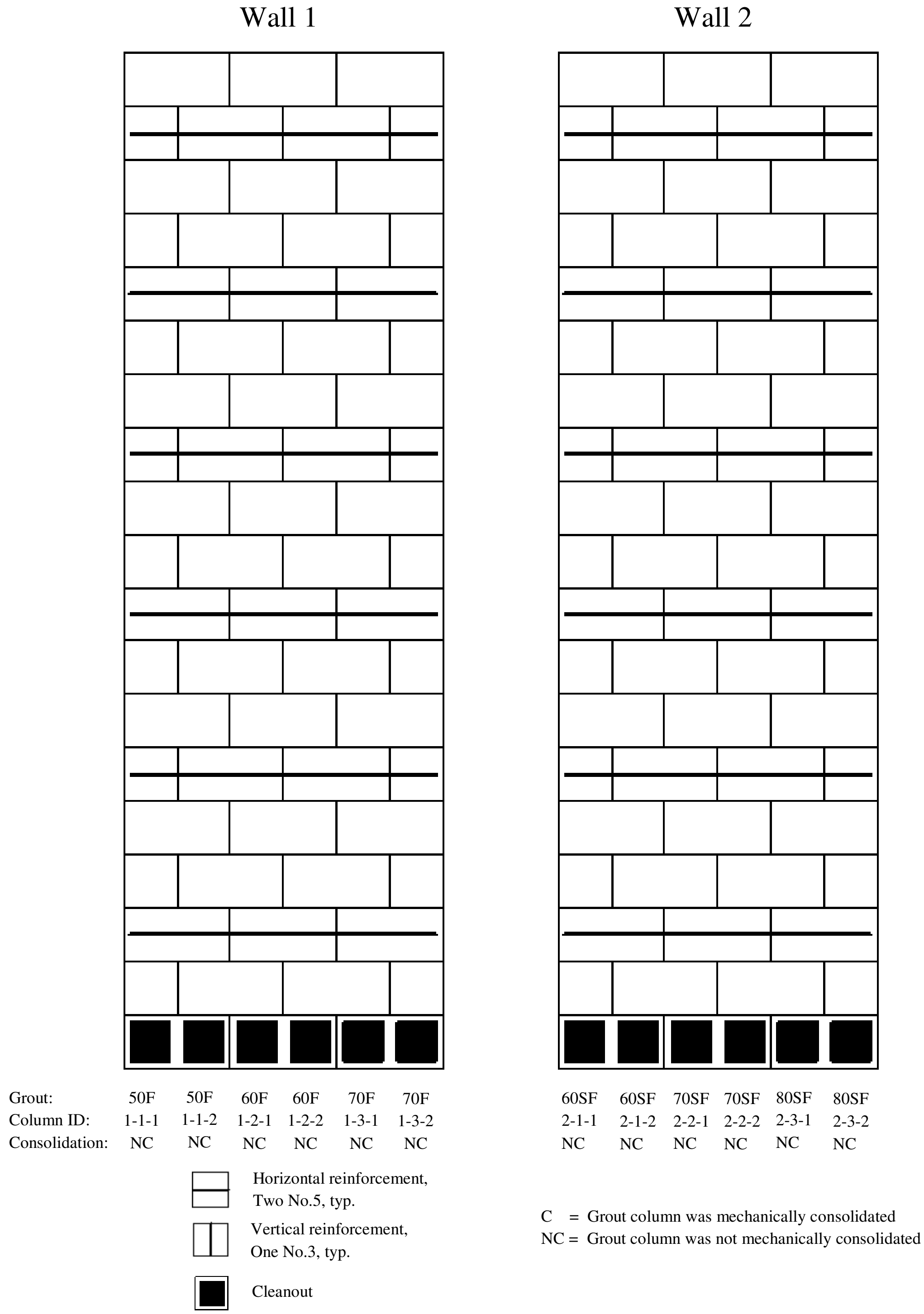


Figure J (1): Wall Configuration Elevations
Source: Author Diagrams

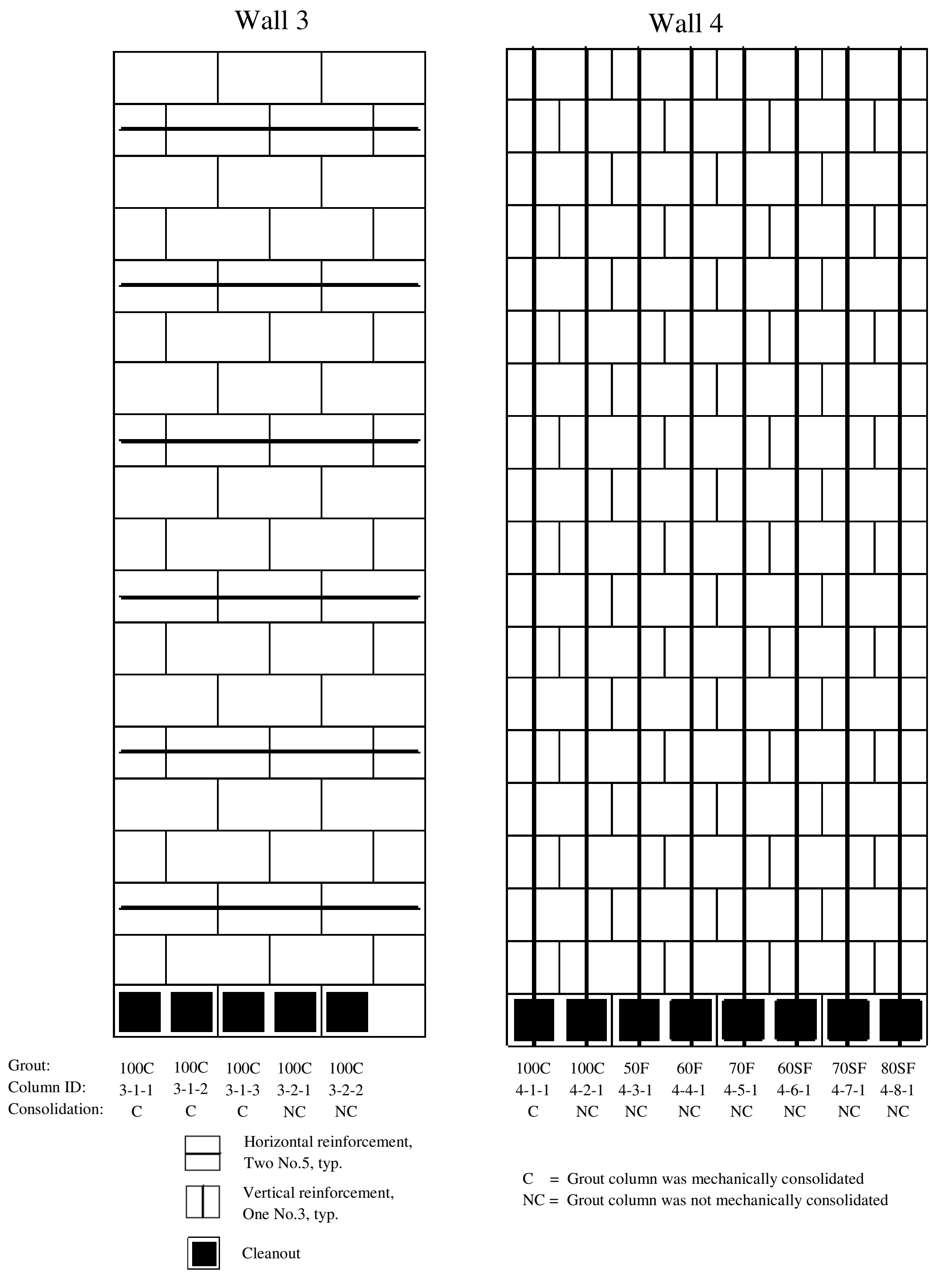


Figure J (2): Wall Configuration Elevations
Source: Author Diagrams

4.4.2 Constructing the Walls

The walls were constructed in an indoor facility, the High Bay Laboratory at California Polytechnic State University in San Luis Obispo, California. Before the first courses of CMUs were positioned, sections of cardboard matching the width and thickness of the walls were placed on the floor. The cardboard served as a membrane between the grout and floor, insuring that a bond between the two would not be made. This was important later in the procedure when the walls were tilted and lowered down in order to help ensure the walls did not crack. Following the design of the wall, the walls were erected by professional masons in one lift, as shown in Figure K.

Figure K: Professional Masons Building Walls 1 and 2
Source: Author Photo

4.4.3 Grouting the Walls

The walls were grouted between 77 to 81 days on site after the walls were erected. The materials were batched by volume and mixed in a mechanical mixer in accordance

with ASTM C 476 as shown in Figure B. A slump test, following ASTM C 143, was conducted for the conventional grouts (shown in Appendix A.5) and a slump flow test, following ASTM C 1611, was conducted for the experimental grouts (shown in Appendix A.6). The grout was transported in five gallon buckets to the top of the walls where it was remixed by hand to ensure the aggregates did not settle during the transportation, as shown in Figure L(1). The grout was poured into the grout column through a funnel at the top, as shown in Figure L(2).

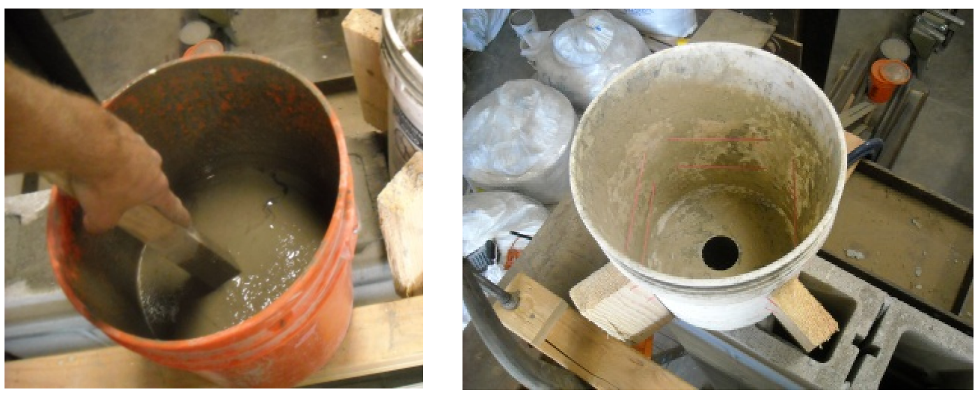


Figure L: (1) Remixing Grout by hand and (2) Grout Funnel Leading into One Grout Column
Source: Author Photos

Each grout column took approximately 30 minutes to complete. A flashlight was used to check if there was any seepage of the grout into the adjacent grout columns. There was no noticeable seepage found for all groutings. For the conventional grout columns with mechanical consolidation, a 13 ft. long, 1 in. diameter, mechanical internal-type vibrator was lowered into the center of the cells and all the way to the bottom of the column before the grout was poured. After approximately one third of the

grout column was poured, the vibrator was turned on, left for 5 seconds, and slowly lifted out one third of the way as shown in Figure M. This process was repeated two more times until the grout column was completely grouted and vibrated. The total time of vibration per grout column was approximately 30 seconds.

Figure M: Mechanical Vibration
Source: Author Photo

The conventional grout columns with mechanical consolidation were grouted and vibrated before the other grouts in the same walls were poured to ensure that the grouts did not receive any form of mechanical consolidation. Table 4 lists the grouting column order.

Table 4: Grouting Schedule for Wall Experiment

Grouting Schedule	
Date	Column Grouting Order Per Day
7/27/2012	1-1-1, 1-1-2, 1-2-1, 1-2-2, 1-3-1, 1-3-2
7/28/2012	3-1-1, 3-1-2, 3-1-3, 4-1-1, 3-2-1, 3-2-2, 4-2-1
7/29/2012	2-1-1, 2-1-2, 2-2-1, 2-2-2, 2-3-1, 2-3-2
7/30/2012	4-3-1, 4-4-1, 4-5-1, 4-6-1, 4-7-1, 4-8-1

4.4.4 Lowering the Walls

The walls were lowered to a horizontal position approximately 70 days after being grouted. The walls were confined by lumber and straps, tilted using a forklift, and lowered using an overhead crane, as shown in Figure N.

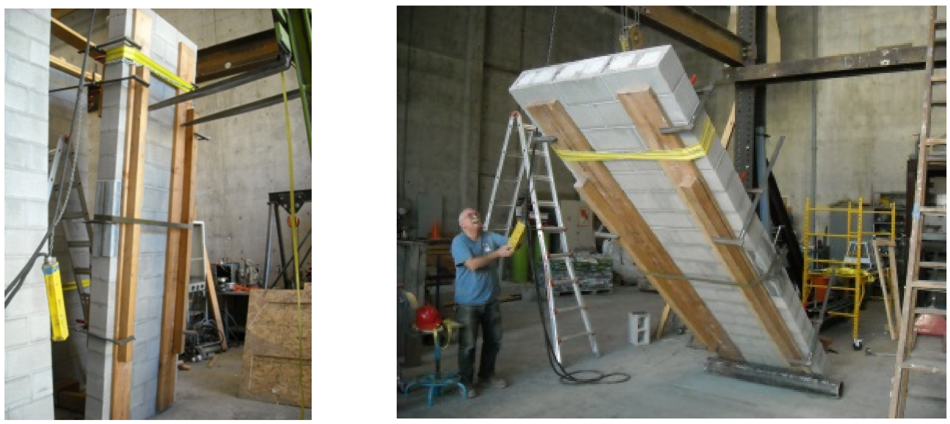


Figure N: (1) Fork Lift Tilting Wall and (2) Overhead Crane Lowering Wall
Source: Author Photos

Once the wall was in a horizontal position, the forklift and overhead crane were used to transport the wall approximately 20 ft. outside of the laboratory, resting on empty CMUs, as shown in Figure O.

Figure O: Walls Resting Horizontally
Source: Author Photo

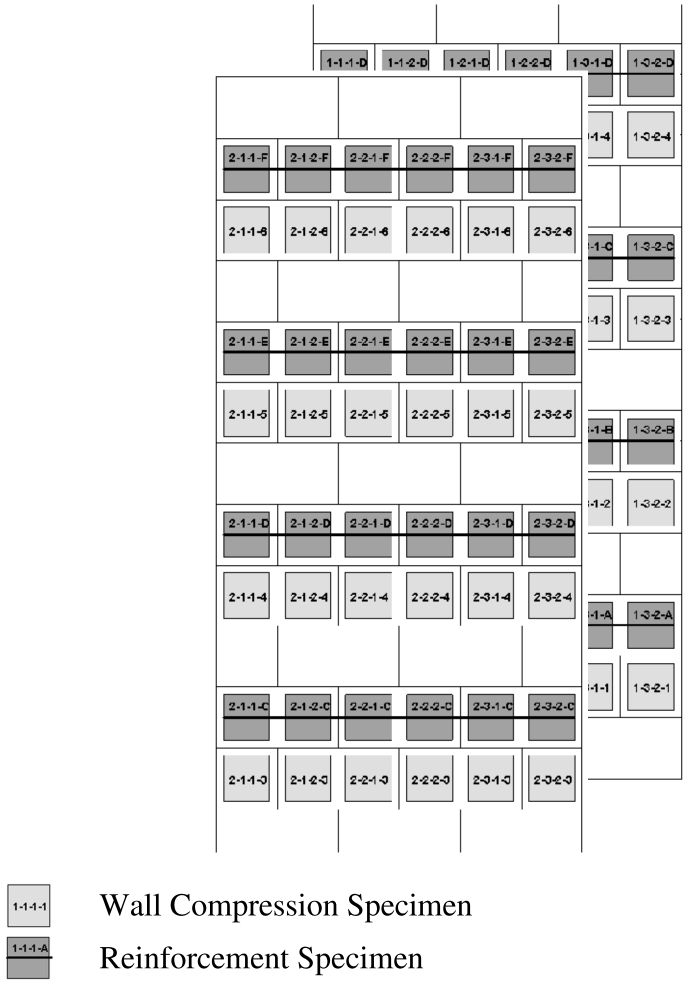
4.4.5 Labeling the Walls

For walls 1, 2, and 3, there were six different heights along the wall where both the wall compression specimens and reinforcement specimens were taken from each grout column. The location of each specimen was identified by a 3-digit grout column ID code, as shown in Figures J(1) and J(2), with an added marker at the end to indicate the height along the column where that specimen came from. For wall compression specimens, the last markers were numbers that varied from 1-6, 1 being the closest to the bottom of the wall and 6 being the closest to the top of the wall. The wall compression specimens were taken at heights of 12, 36, 60, 84, 108, and 132 inches from the bottom of the wall. For the reinforcement specimens, the last markers were letters in alphabetical order from A-F, A, starting closest to the bottom of the wall and, F, nearest the top. The reinforcement specimens were taken at heights of 20, 44, 68, 92, 116, and 140 inches from the bottom of the wall.

For Wall 4, there were three different heights along the wall where rebar pullout specimens were taken. The additional last digit was marked number 1 for specimens taken at 16 in., 2 for specimens taken at 64 in., and 3 for specimens taken at 128 in. from the bottom of the wall. Locations of the specimens from the walls are shown in Figures P(1) and P(2), on the following pages.

Wall 1

Wall 2



Wall Compression Specimen

Reinforcement Specimen

Figure P (1): Location of Specimens
Source: Author Diagram

Wall 3

Wall 4

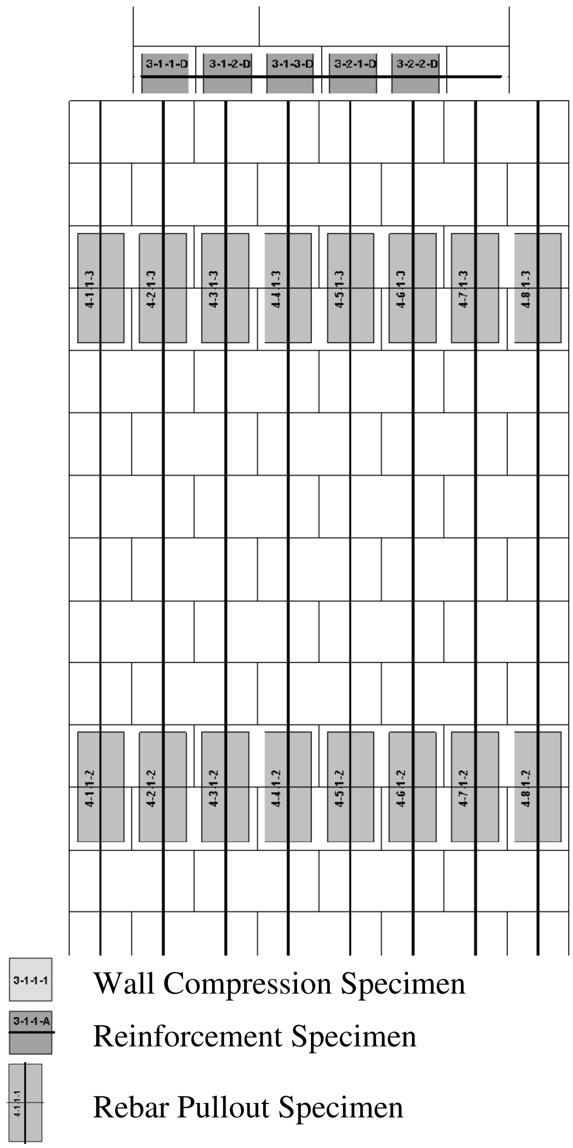


Figure P (2): Location of Specimens
Source: Author Diagram

4.4.6 Cutting the Walls

The walls were cut by a demolition contractor using 16 and 18 in. diameter diamond bladed saws and a 14 in. diameter hydraulic ring saw in order to retrieve the test specimens. For walls 1, 2, and 3, a horizontal cut across each course was made, as shown

in Figure Q(1). For wall 4, two horizontal cuts were made to split the wall into thirds and vertical cuts were made in-between each grout column, as shown in Figure Q(2).

Figure Q: Cutting Walls: (1) Horizontally and (2) Vertically
Source: Author Photos

For walls 1, 2, and 3, a hand saw with a 14 in. diameter diamond blade was used to cut through the horizontal reinforcement at the mortar joints in order to separate each CMU, as shown in Figure R.

Figure R: Cutting through Reinforcement Using a Hand Saw
Source: Author Photo

A 20 in. diamond blade wet saw was used to cut the wall compression specimens into 4x4x8 in. (nominal) grout units, as shown in Figure D, and the reinforcement specimens were cut once vertically across the middle of each grout cell containing reinforcement in order to see the consolidation characteristics adjacent to the reinforcement. In total, 96 wall compression test specimens and 96 reinforcement specimens were retrieved from the walls, as shown in Figure S.

Figure S: (1) Side View of Wall Compression Specimen and (2) Reinforcement Specimen
Source: Author Photos

For wall 4, the unwanted grout in each rebar pullout section was chiseled away from the reinforcement using a jack hammer and a hand chisel in order to prepare specimens for rebar pullout test, as shown in Figure T.

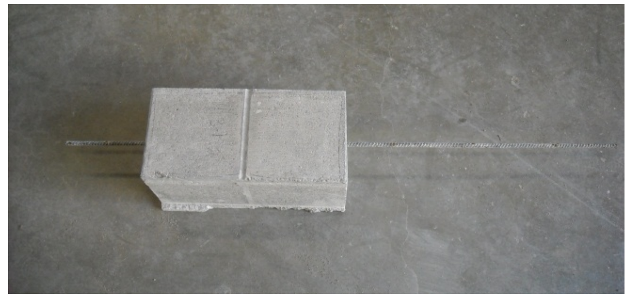



Figure T: (1) Chiseling Away Grout from Reinforcement and (2) Rebar Pullout Specimen
Source: Author Photos

4.4.7 Testing of Specimens

4.4.7.1 Wall Compression Tests. The retrieved wall compression specimens were capped and prepared for testing in accordance with ASTM C 1552, shown in Figure E(1). The specimens were tested in compression, after 130 day of curing, in accordance with ASTM C 1019, as shown in Figure U.

Figure U: Compression Testing of Wall Compression Test Specimen 2-1-2-6
Source: Author Photo

4.4.7.2 Wall Consolidation Inspection. The consolidation characteristics (segregation of aggregates and presence of air voids) were visually examined from the wall compression and reinforcement specimens. The sizes of air voids were recorded for (1) the top view (before final cutting) from the wall compression specimens (indicated consolidation around the mortar fins shown in Figure V), (2) the side view from the retrieved wall compression specimens (indicated consolidation on specimen's surface shown in Figure S(1)), and (3) the reinforcement specimens (revealed consolidation adjacent to the reinforcement shown in Figure S(2)).

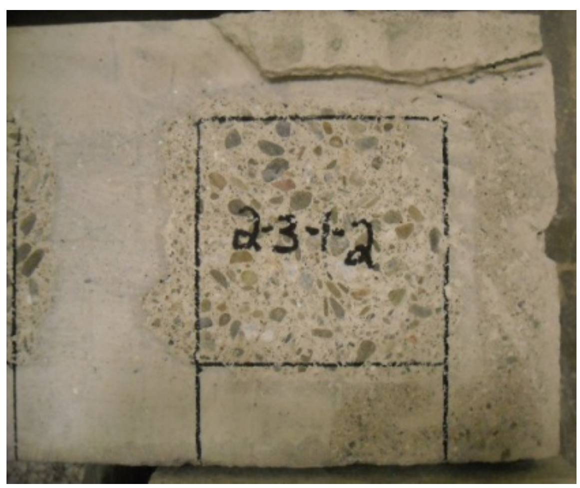


Figure V: Top View of Wall Compression Specimen
Source: Author Photo

The reinforcement specimens were graded on an acceptance level modified from shotcrete core consolidation grades (ACI 560.2-95 1995), as shown in Table 5.

Table 5: Modified Shotcrete Core Consolidation Grades

Location of voids	Visually Inspected Diameter of Air Voids (Inches)				
	Grade				
	1	2	3	4	5
General	≤ 1/8	≤ 3/8	≤ 3/8	≤ 3/8	> 3/8
Near Reinforcement	None	≤ 1/2	≤ 5/8	≤ 1	>1

Shotcrete is concrete or mortar conveyed through a hose and pneumatically projected at high velocity onto a surface. Shotcrete is consolidated by material impact and quality control procedures must be established to assure that the final product function as designed (ACI 506.2-95 1995). The acceptance of consolidation quality is obtained from drilled cores containing reinforcement and visually inspected for compliance with the specified shotcrete core grades. Determination of grade is computed by taking the mean of a minimum of three test specimens. A mean grade of 2.5 or less is acceptable and individual shotcrete cores with a grade greater than 3 are unacceptable.

4.4.7.3 Rebar Pullout Tests. The rebar pullout specimens were tested at approximately 170 days of curing in accordance with ASTM C 900 Standard Test Method for Pullout Strength of Hardened Concrete, as shown in Figure W.

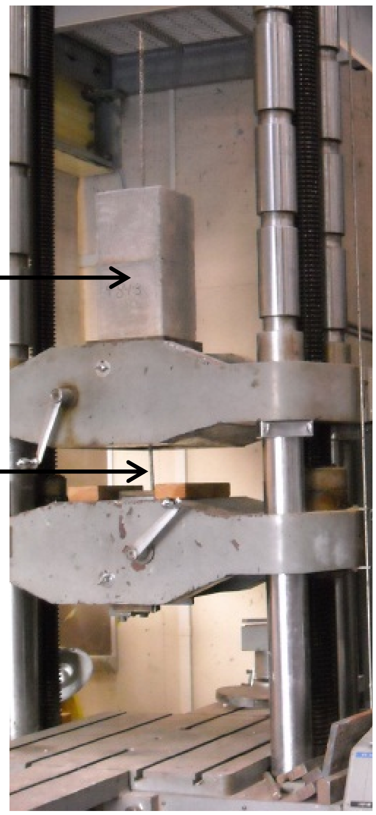


Figure W: Rebar Pullout Test
Source: Author Photo

5.0 RESULTS

5.1 Slump/Slump Flow

The conventional grout was determined to have a water-to-cement ratio of 1.375 (by volume), which provided an average slump of 9.75 inches (presented in Appendix A.1), following ASTM C 143.

The experimental grouts were found to have a slump flow between 24 to 30 inches for all mixtures, following ASTM C 1611; therefore, satisfying one of the requirements to be considered a self-consolidating grout according to ASTM C 476. For both types of cement replacement (fly ash and fly ash/GGBFS), it was found that, in general, the slump flow increased in diameter as the amount of cement in the mixture decreased, as shown in Figure X.

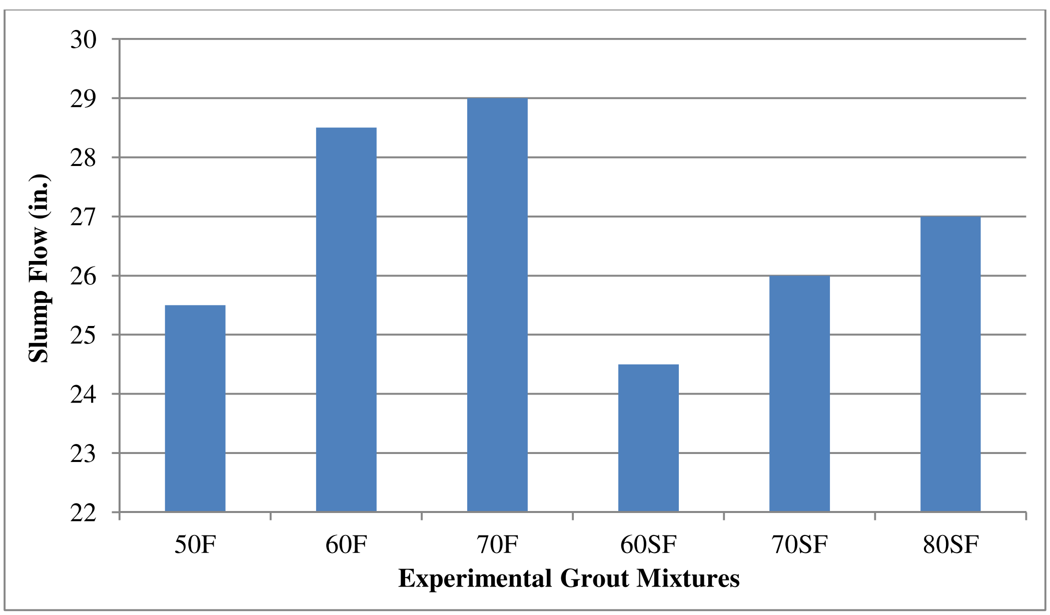


Figure X: Average Slump Flows of Experimental Grouts
Source: Author Figure

All experimental grouts were found to have a VSI of 1 (Stable) as there was no evidence of segregation but a slight bleeding was observed as a sheen on the grout mass. None of the mixtures were considered unstable because there was no noticeable mortar halo and/or aggregate pile in the center of the grout mass. The slump flow results are presented in Appendix A.2, and an example photograph of the slump flow is shown in Figure Y. Providing a VSI of 1 satisfied another requirement of ASTM C476 for the experimental grouts to be considered self-consolidating grouts.

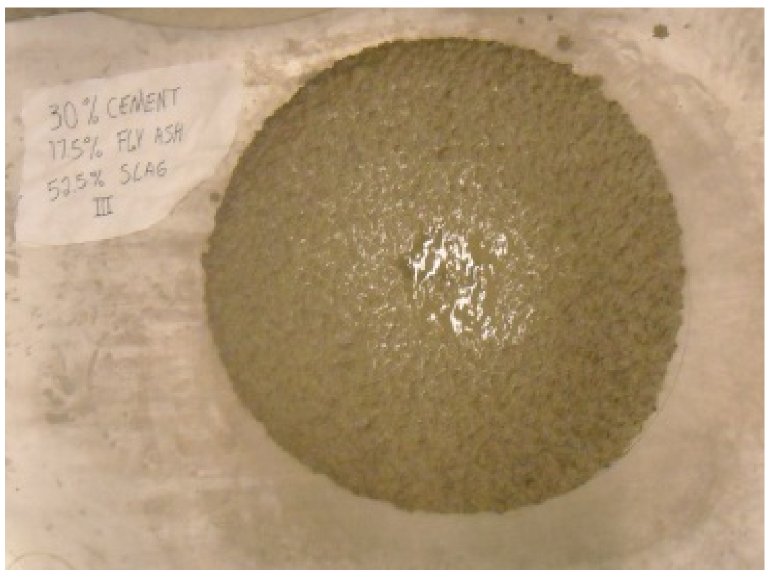


Figure Y: Slump Flow Picture of 70SF Batch 3
Source: Author Photo

5.2 The Compression Experiment

For each of the seven grout mixtures (100C, 50F, 60F, 70F, 60SF, 70SF, 80SF), three specimens were tested in compression at each curing time (7, 14, 28, 42, 56, and 130 days) in accordance with the applicable requirements of ASTM C 1019. A net compressive strength was determined for each specimen. From the net compressive

strength of each specimen, a corrected net compressive strength was determined by multiplying by a correction factor based on the height-to-thickness ratio of the specimen, from Table 1 of ASTM C 1314 Standard Test Method for Compressive Strength of Masonry Prisms, in order to better account for the load carrying capacity. The corrected net compressive strengths for each group of three specimens were averaged and are presented in Appendix B. These averaged corrected net compressive strengths are shown in Figure Z.

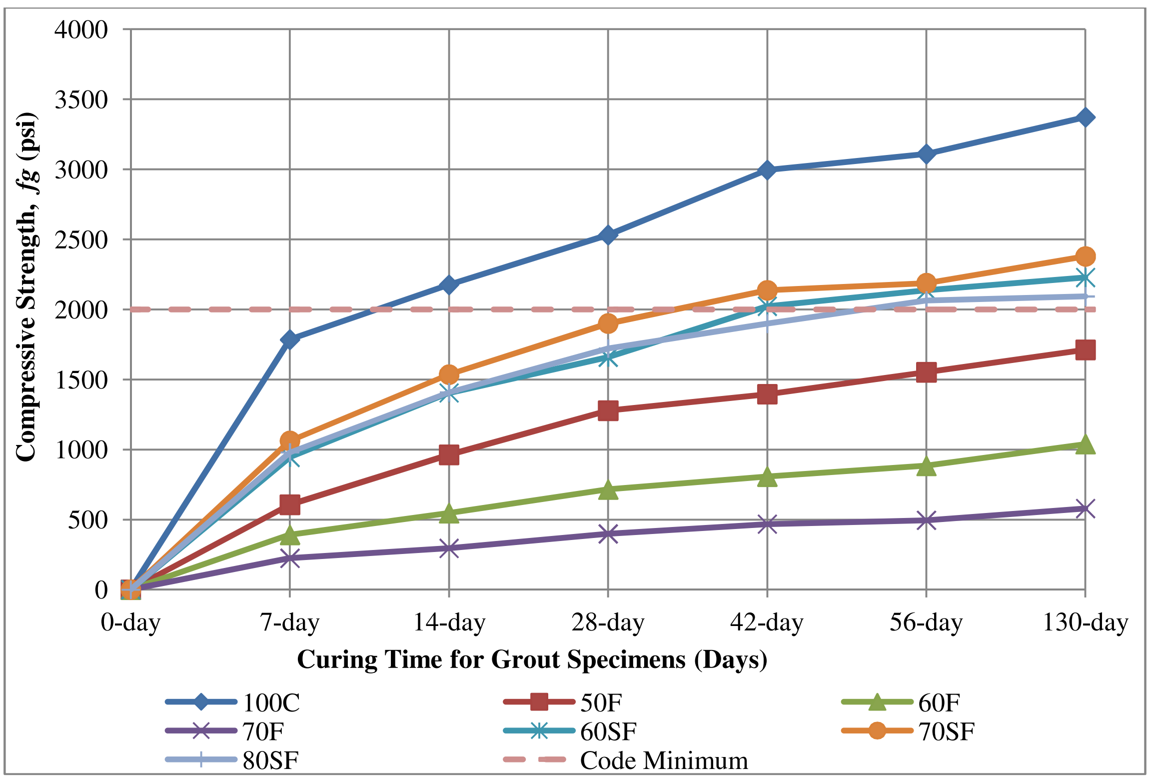


Figure Z: Average Corrected Net Compressive Strength of Grouts from the Compression Experiment
Source: Author Figure

The tested grout compressive strengths are compared to the minimum requirements of the International Building Code (IBC 2012) and ASTM C 476, in order to determine their feasibility. The minimum requirements, call for the grout to have a compressive strength of at least 2,000 psi after 28 days of curing. Figure Z illustrates that only the convention grout, 100C, met this requirement. By the tested cure time of 56 days, grout mixtures 60SF, 70SF, and 80SF passed the 2,000 psi minimum. Grout mixtures 50F, 60F, and 70F did not meet this requirement through the tested cure time of 130 days.

5.3 Wall Experiment

5.3.1 Wall Compression Tests

Grout compression specimens cut from various heights along walls 1, 2, and 3 were tested in accordance of ASTM C 1019. Corrected net compressive strengths were determined and are presented in Appendix C. The curing time of these specimens were 130 days, matching the longest tested curing time of the compression specimens from the Compression Experiment. The wall compression test specimens were normalized by the average compressive strength results from the Compression Experiment at the curing time of 130 days, as provided in Appendix D. The normalized data demonstrates the similarity of compressive strengths achieved between The Wall Experiment and The Compression Experiment.

The compression test results from Wall 1 of the Wall Experiment specimens are shown in Figure AA, on the next page (data provided in Appendix C).

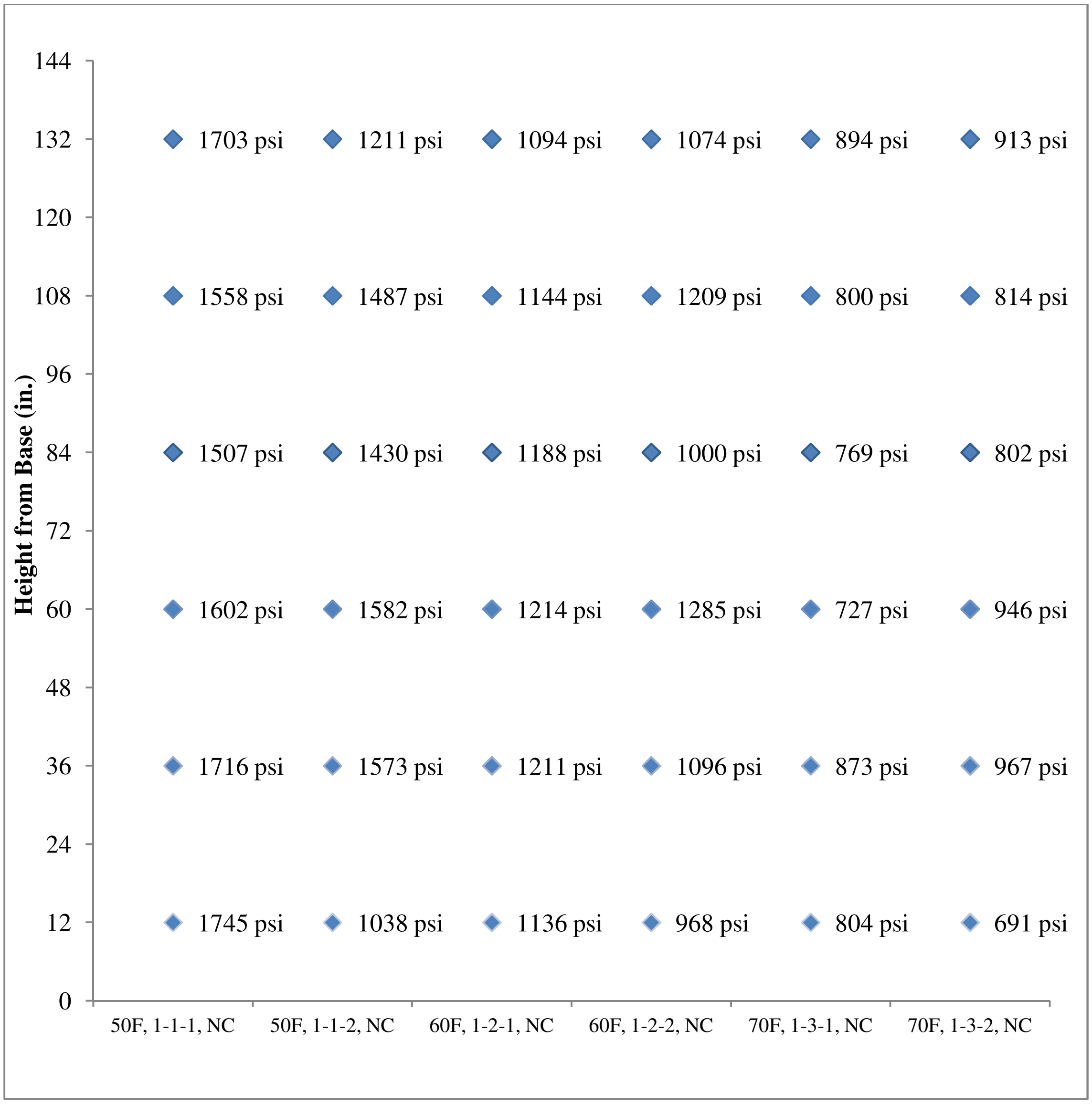


Figure AA: Wall 1 Grout Specimen's Corrected Net Compressive Strength Test Results
Source: Author Figure

The compression test results from Wall 2 of the Wall Experiment specimens are shown in Figure BB (data provided in Appendix C).

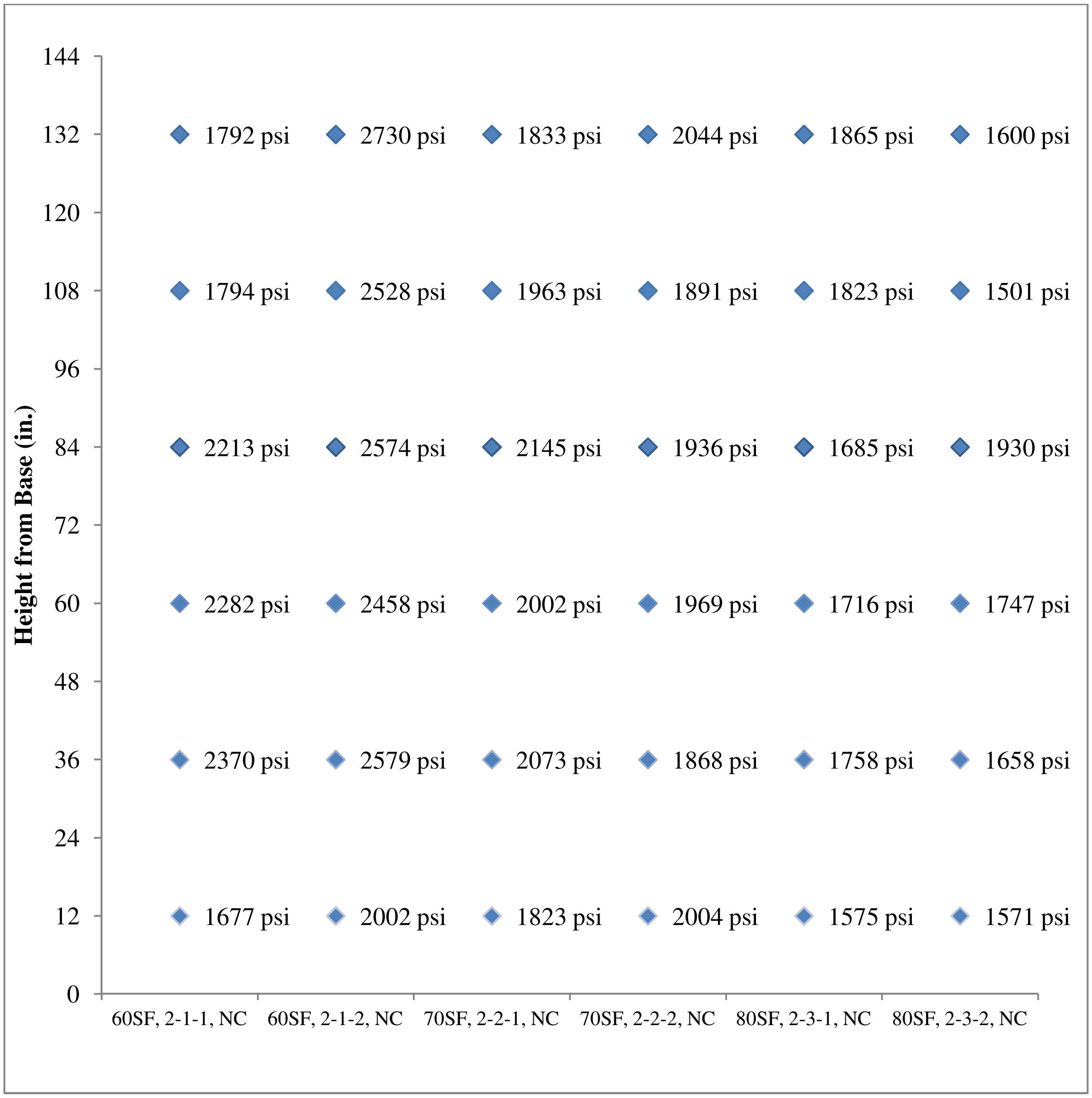


Figure BB: Wall 2 Grout Specimen's Corrected Net Compressive Strength Test Results

Source: Author Figure

The compression test results from Wall 3 of the Wall Experiment specimens are shown in Figure CC (data provided in Appendix C).

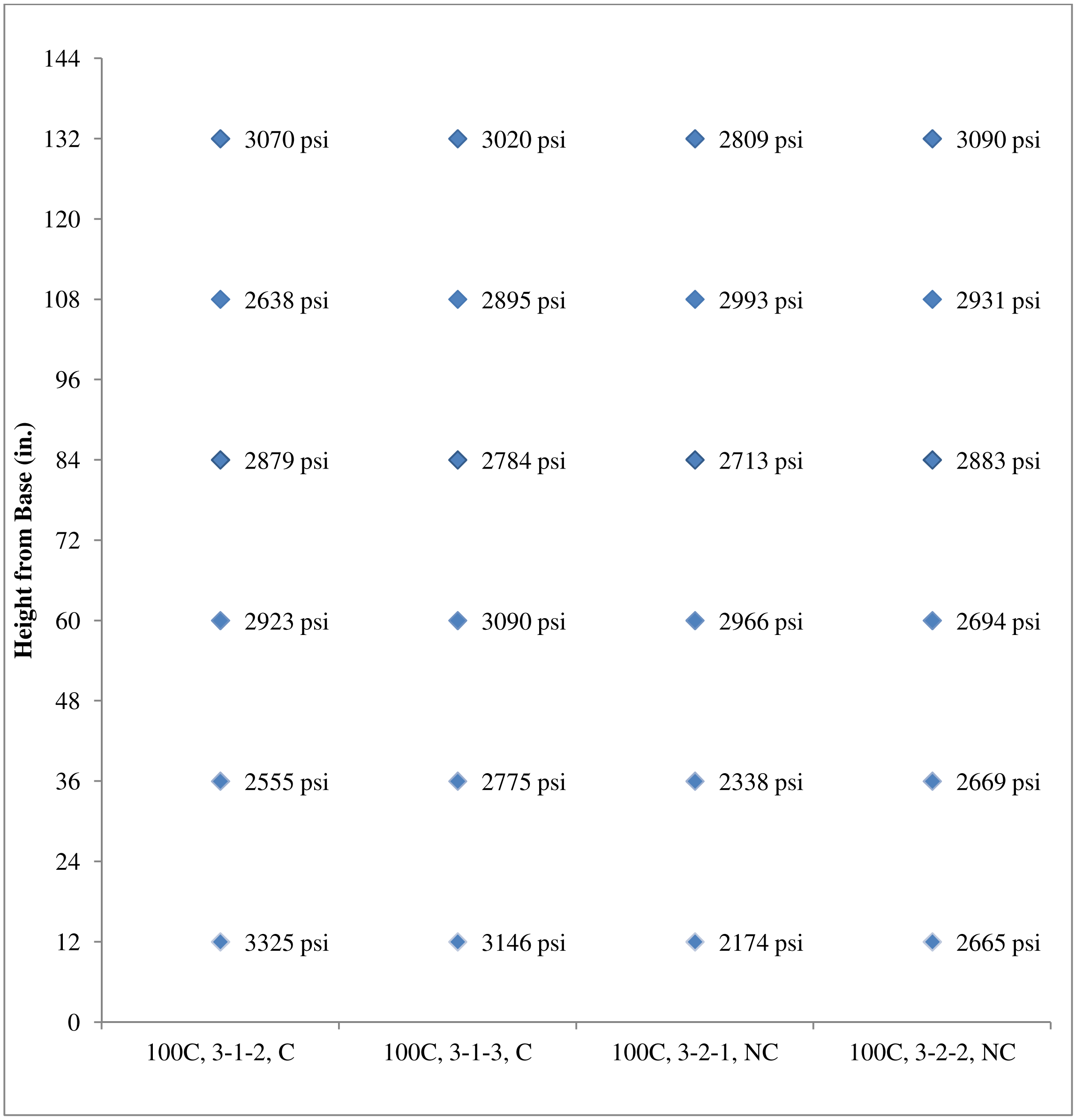


Figure CC: Wall 3 Grout Specimen's Corrected Net Compressive Strength Test Results

Source: Author Figure

The compressive strength results for the grout specimens with identical data sets combined (averaged compressive strength of specimens with the same grout type and at the same height along the wall), are shown in Figure DD (data found in Appendix D).

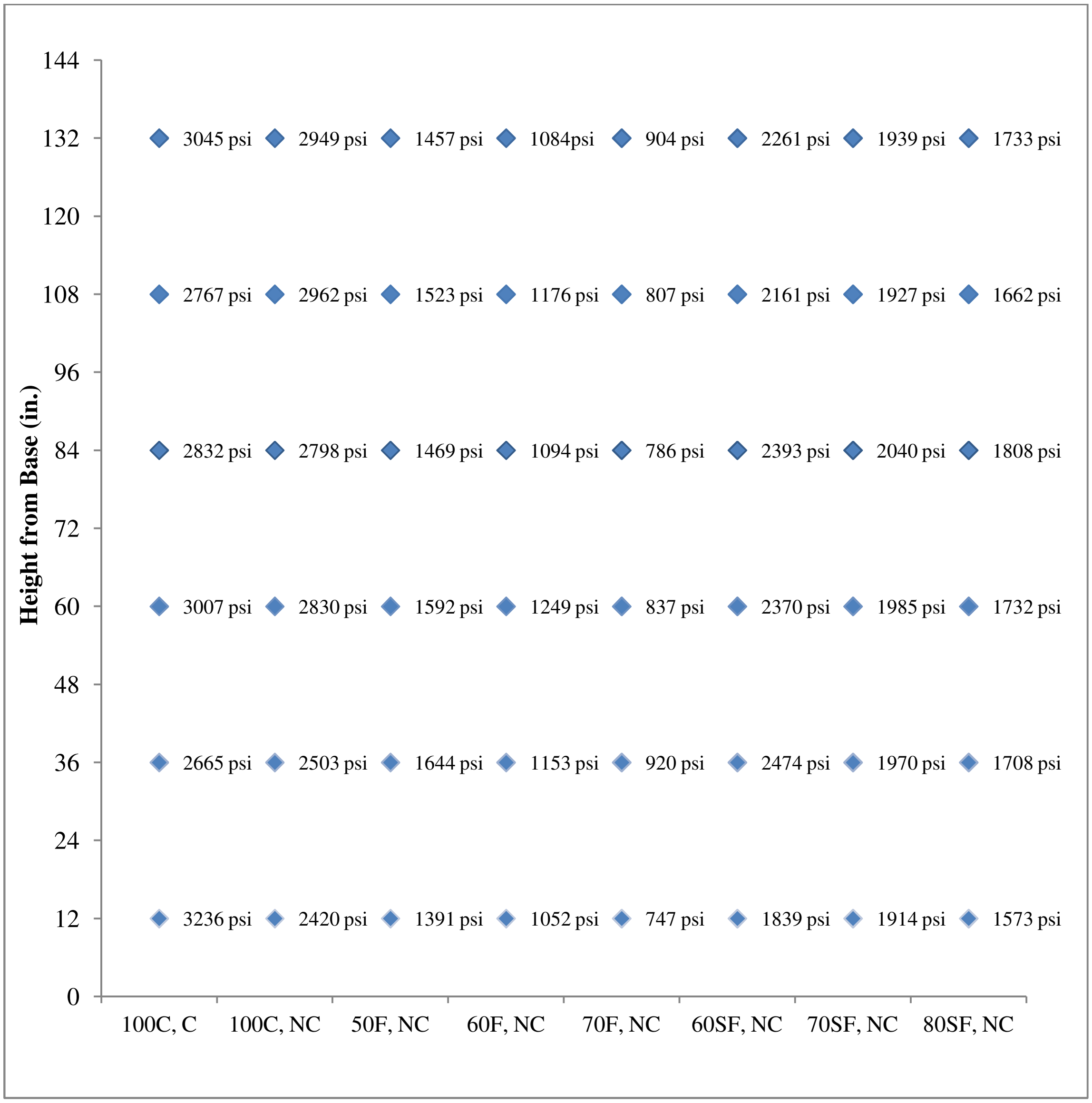


Figure DD: Compressive Strength Test Results of the Identical Data Sets Combined
Source: Author Figure

The average corrected net compressive strengths of each grout mixture (over the entire wall height) are shown in Figure EE (data found in Appendix D).

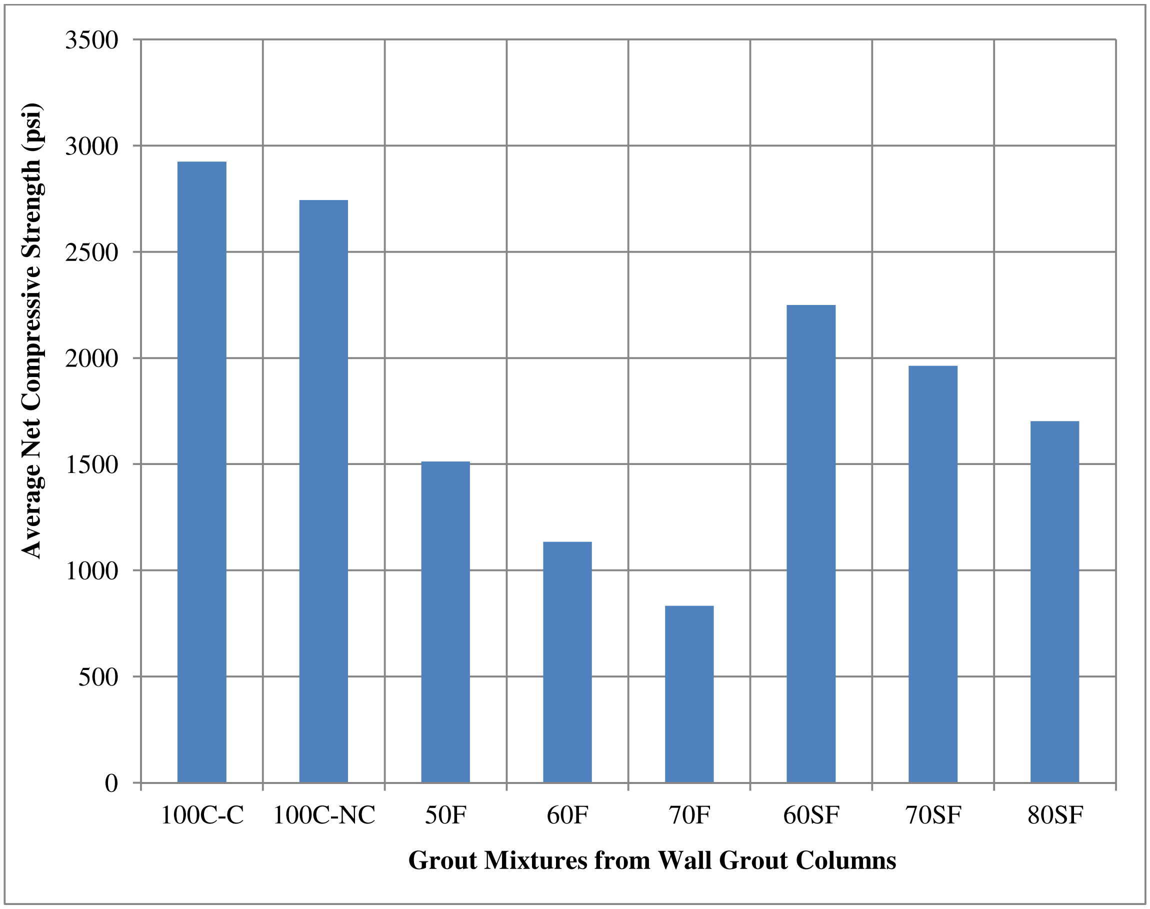


Figure EE: Average Corrected Net Compressive Strengths of Grout Mixtures along the Entire Height of the Wall from the Wall Experiment after 130 Days of Curing
Source: Author Figure

5.3.1.1 Effect of Mechanical Consolidation on Compressive Strength of Conventional Grout. The compressive strengths from wall 3 provide a direct comparison of mechanical consolidation (100C-C) to no mechanical consolidation (100C-NC) for conventional grout. The data summarized in Table 6 indicates that the differences between the consolidated and nonconsolidated compressive strengths are not significant. The overall average of all compressive strengths for the conventional grout nonconsolidated was a 6% decrease in compressive strength from the conventional grout consolidated.

Table 6: Difference in Conventional Grout Compressive Strength Due to Mechanical Consolidation

Height from Base (in.)	Average Corrected Net Compressive Strength of 100C-C (psi)	Average Corrected Net Compressive Strength of 100C-NC (psi)	NC % increase or decrease over C
132	3045	2949	-3%
108	2767	2962	7%
84	2832	2798	-1%
60	3007	2830	-6%
36	2665	2503	-6%
12	3236	2420	-25%

5.3.1.2 Comparing the Corrected Net Compressive Strengths of the Wall Experiment and the Compression Experiment. The average net corrected compressive strength from each mixture in the Wall Experiment is compared to the average net corrected compressive strength from the Compression Experiment. Both experiments are compared on compressive strength tests from 130 days of curing. The data in Table 7 indicates there is a moderate correlation between the two experiments.

Table 7: Difference in Net Corrected Compressive Strength of the Wall Experiment and Compression Experiment after 130 Days of Curing

Grout Mixture	Average Corrected Net Compressive Strength of Wall Experiment (psi)	Average Corrected Net Compressive Strength of Compression Experiment (psi)	% increase or decrease of Wall Experiment over Compression Experiment
100C-C	2925	3372	-13%
100C-NC	2744	3372	-19%
50F	1513	1712	-12%
60F	1135	1039	9%
70F	833	579	44%
60SF	2250	2228	1%
70SF	1963	2379	-17%
80SF	1702	2093	-19%

5.3.1.3 Comparing Compressive Strengths with Visual Examination of Air Voids on Specimens. The top and side profiles of the compression specimens were visually examined and their air voids were measured, as shown in Appendix E. For all specimens and their profiles, no segregation of aggregates were noticed. Since the air voids were only examined on the surface of the compression specimens, the interior air voids of the specimens were unknown. Also, from the top profile, air voids around the mortar fins were recorded. Since the compression specimens were cut from the center of the grout columns, the imperfections around the mortar fins were not a part of the compression tests and had no influence on the tested compressive strengths.

Some of the compression specimens taken from the same mixture and height, but differing grout columns, had similar size air voids on the surface but their compressive strength would vary significantly. This indicates that the lower compressive strength specimens may have had larger air voids in their interior than exterior.

5.3.2 Consolidation Characteristics

The consolidation characteristics (segregation of aggregates and presence of air voids) were visually examined from cuts made throughout each grout column. The consolidation characteristics from the wall compression specimens are provided in Appendix E, and the consolidation characteristics and grades from the reinforcement specimens are provided in Appendix F.

All specimens showed no sign of segregation of aggregates and there was not a significant change in the size of air voids along the height of each grout column.

From inspection of the wall compression specimens, all grouts were noticed to have an average of 1/16 to 1/8 inch diameter air voids located along the sides sections and next to the mortar fins of the top sections. There were two experimental specimens that had air voids greater than 3/8 inch in diameter and would qualify as Grade 5 or unacceptable according to the modified shotcrete consolidation grades in Table 5.

Each reinforcement specimen was graded on an acceptance level from Table 5. The average grades for each mixture are presented in Figure FF.

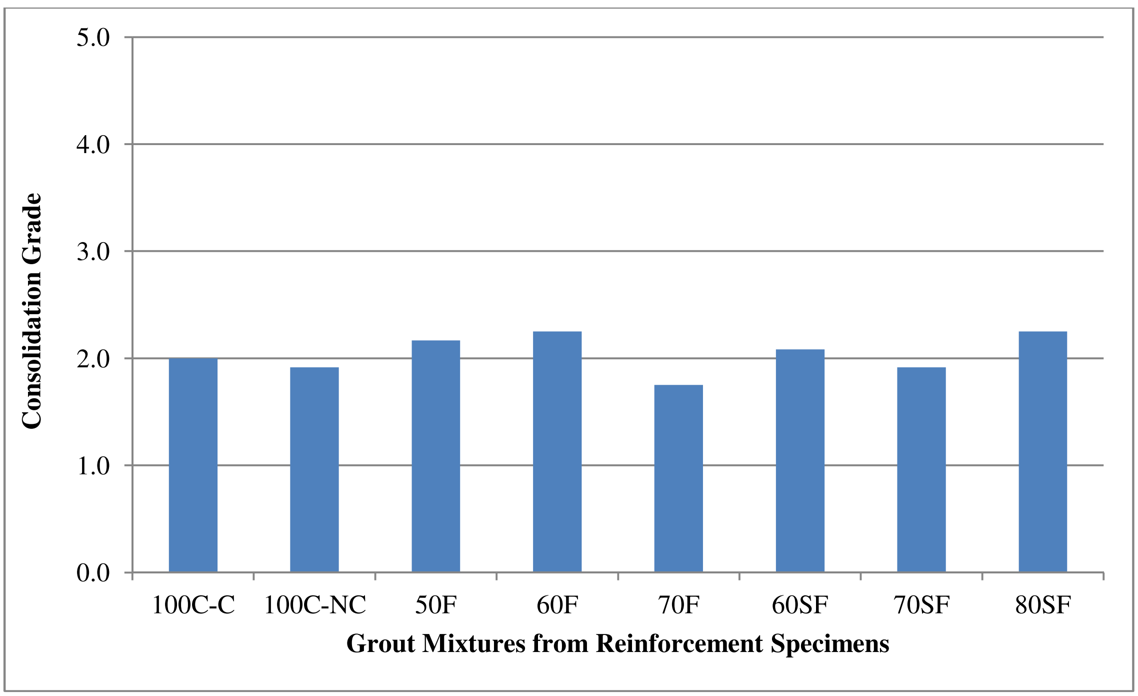


Figure FF: Average Consolidation Grade for Each Grout Mixture
Source: Author Figure

The mean consolidation grades for all grouts were less than 2.5, indicating that the consolidations were acceptable. There were five out of 96 total reinforcement

specimens that were not acceptable; three specimens (60SF and two 80SF) were Grade 4, and two specimens (50SF and 60SF) were Grade 5.

Examples from the specimens visually inspected are shown in Figures GG, HH, and II.

Figure GG: Top View of Wall Compression Specimen 2-3-1-6 before Final Cutting
Source: Author Photo

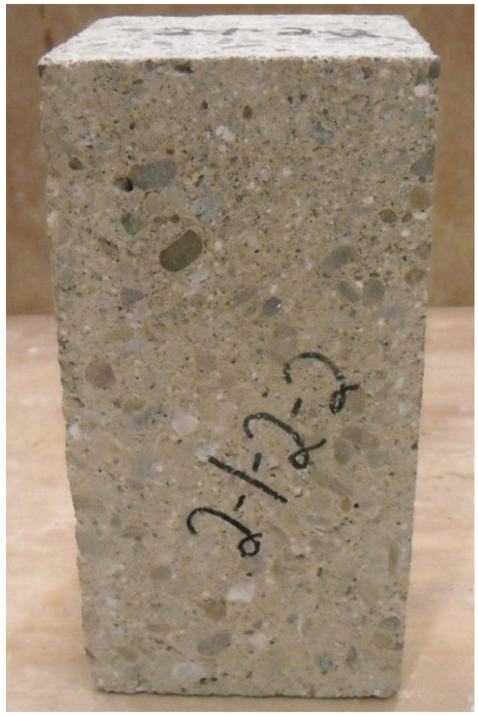


Figure HH: Side View of Wall Compression Specimen 2-1-2-2
Source: Author Photo

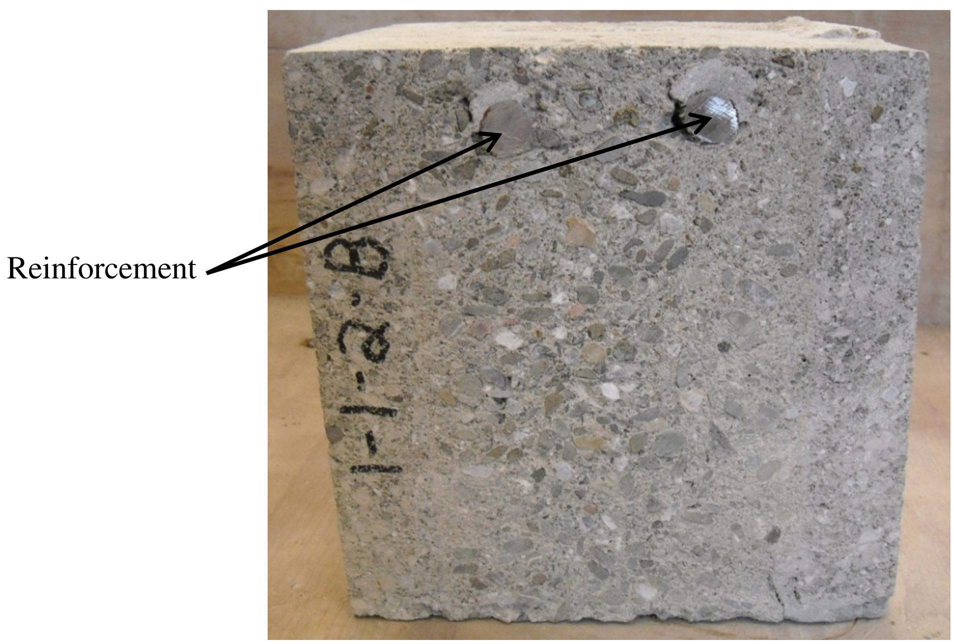


Figure II: Cross Section of Reinforcement Specimen 1-1-2-B
Source: Author Photo

5.3.3 Rebar Pullout

Three rebar pullout specimens per grout mixture were tested. All specimens failed from the reinforcement pulling out of the grout, as shown in Figure JJ. The average bond strength for each mixture is shown in Figure KK and is provided in Appendix G.1. In order to determine if the grouts had the same relationship between compressive strength and bond strength, as in Equation 2, the average bond strength for each mixture was normalized to the square root of the average net corrected compressive strengths from The Wall Experiment, as provided in Appendix G.2.

Figure JJ: Failure mode: Reinforcement Pull Out of Grout
Source: Author Photo

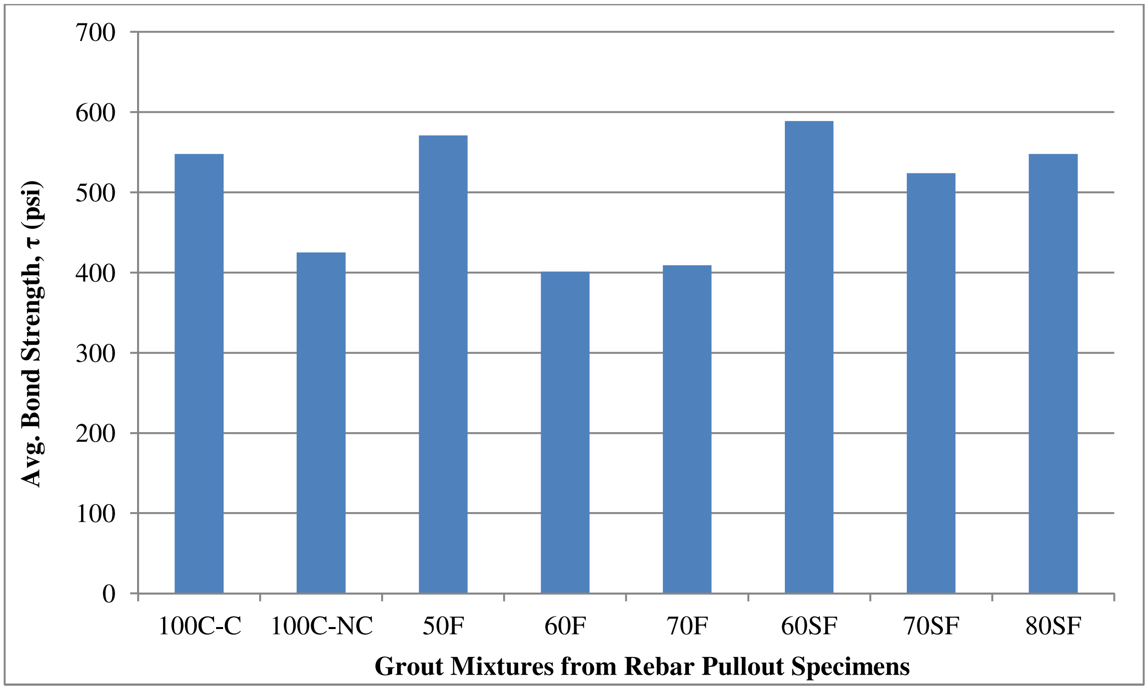


Figure KK: Average Bond Strength for Each Grout Mixture
Source: Author Figure

In all of the rebar pullout specimens, the reinforcement pulled out of the grout before the reinforcing bars could yield. Since Equation 3 requires the reinforcement to yield in order to determine the minimum development length, the equation was modified, as shown in the equation

$$l_d = \frac{0.13 d_b^2 (\frac{T}{A_s}) \gamma}{K\sqrt{f_g}} \quad , \qquad \text{Eq.4}$$

Where
- l_d is the development length of straight reinforcement (in.),
- d_b is the nominal diameter of reinforcement (in.),
- T is the tensile axial force in the reinforcement (lb.),
- A_s is the effective cross-sectional area of reinforcement (in.^{2}),
- γ is the reinforcement size factor (dimensionless),
- K is the dimension used to calculate reinforcement development (in.), and
- f_g is the compressive strength of grout (psi).

Even though the reinforcement did not yield, it still experienced an amount of stress, f_s, at the applied load, T. Also, Equation 3 assumes a conventional grout compressive strength after 28 days of curing because the compressive strength should be above the code minimum of 2000 psi. From The Compression Experiment, the conventional grout passed the minimum after 28 day of curing, so the compressive strength, f_g, after 28 days of curing was used in Equation 4. The fly ash and GGBFS replacement grouts all passed the code minimum after 56 days of curing, while the fly ash replacement grouts were not close to the minimum through 130 days of curing; therefore, the compressive strength of the fly ash, and fly ash and GGBFS replacement grouts after 56 days of curing were used in Equation 4 (provided in Appendix G.3).

The required theoretical development lengths of reinforcements, l_d, found from Equation 4 were normalized to the actual embedment lengths, l, of the rebar pullout specimens, as shown in Figure LL. The normalized values less than 1.0 indicate that minimum development length for the applied load was achieved from the specimen, whereas values greater than 1.0 indicate that minimum development lengths for the applied load exceeded the embedment length of the specimen.

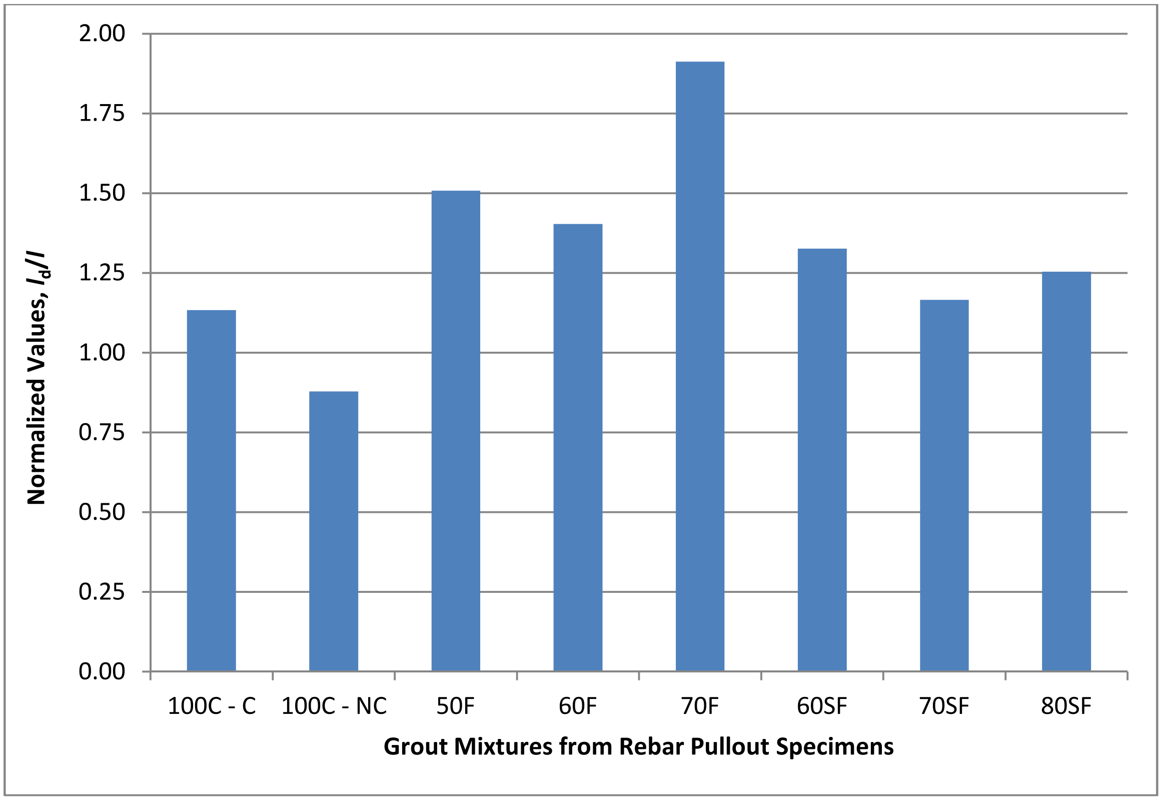


Figure LL: Average per Mixture of the Theoretical Development Lengths of Reinforcements Normalized to the Actual Embedment Lengths of the Rebar Pullout Specimens

Source: Author Figure

6.0 CONCLUSIONS

The purpose of this thesis was to investigate if high Type F fly ash and/or GGBFS replacement of Portland cement in grout, without the use of admixtures and mechanical consolidation, can function as self-consolidating grout. After the completion of the experimental testing performed, the following conclusions were made.

Overall, the Type F fly ash and GGBFS replacements of Portland cement (60SF, 70SF, and 80SF) can function as self-consolidating grouts (with delayed curing time of 56 days), whereas the Type F fly ash replacements of Portland cement (50F, 60F, and 70F) are not viable self-consolidating grouts.

The experimental grouts, fly ash and/or GGBFS replacement of Portland cement satisfied the flow requirements of a self-consolidating grout mixture. All experimental grouts specimens were visually examined to have no segregation of aggregates and there were no significant variations of air void sizes throughout the height of each grout column. The experimental grouts were observed to have no significant differences in consolidation characteristics compared to the mechanically consolidated conventional grout. The average consolidation grades for all grout mixtures were less than 2.5, indicating that the consolidations were acceptable.

In order to be considered a self-consolidating grout according to ASTM C 476, the grout must provide a slump flow between 24 to 30 inches, a VSI of no more than 1, and a minimum compressive strength of 2000 psi after 28 days of curing. All experimental grouts met the slump flow and VSI requirements. From The Compression

Experiment, the experimental grout mixtures where Portland cement was replaced with Type F fly ash and GGBFS (60SF, 70SF, and 80SF) met the minimum compressive strength requirement after 56 days of curing rather than 28 days. The compressive strengths of these specimens were significantly lower than the conventional grout but still met the code minimum. The experimental grout mixtures where Portland cement was replaced with Type F fly ash alone (50F, 60F, and 70F) does not appear to be a viable grout alternative because of their low compressive strength.

From the Wall Experiment, the results on compressive strengths of the grouts in produced similar results to the Compression Experiment for a curing time of 130 days, affirming the validity of the data obtained. Also, there was not any significant variation in compressive strengths of the samples taken from differing heights along the walls. The grout mixtures with fly ash and GGBFS replacement of cement after 130 days of curing were close to the 2000 psi minimum for both experiments. From the Wall Experiment, only the 60SF met the minimum compressive strength requirement and although the 70SF and 80SF did not differ significantly from each experiment, they did not met the requirement. The experimental grout mixtures where Portland cement was replaced with Type F fly ash alone did not meet the minimum compressive strength requirement for both experiments; therefore, they do not appear to be a viable grout alternative.

The average bond strengths from the rebar pullout specimens normalized to the square root of the average net corrected compressive strengths from The Wall

Experiment match Equation 2 adequately. This indicates that the self-consolidating grouts share a similar relationship as the conventional grout, between their compressive strength and bond strength. The code (MSJC 2011) requires that the reinforcement must be anchored so as to fully develop the reinforcing bar to its yield stress. From required development lengths of reinforcement normalized to the embedment lengths of the rebar pullout specimens, as shown in Figure LL, the fly ash and GGBFS replacement grouts had similar normalized values as the consolidated conventional grout, whereas the fly ash replacement grouts had normalized values that were significantly greater. Therefore, the fly ash replacement grouts do not meet the code minimum development lengths required.

REFERENCES

(ACI 506.2-95 1995) Specification for Shotcrete, American Concrete Institute, Michigan: 1995. Print.

(Bonen and Shah 2005) Bonen, David, and Surendra Shah. "Fresh and Hardened Properties of Self-Consolidating Concrete." *Progress in Structural Engineering and Materials*. (2005): Vol. 7.1: 14-26. Web. 18 April 2011.

(Bradfield 2011) Bradfield, Maribeth. "High Supplemental Cementitious Material (SCM) Grout Phase 2 and 3 Research." *Masonry Chronicles*. (2011). Web. 1 May 2011.

(Fang and Labi 2006) Fang, Chuanxin, and Samuel Labi. "Evaluating the Static Segregation Resistance of Hardened Self-Consolidating Concrete using Image Processing Technology". *Transportation Research Board*. (2006). Web. 17 May 2011.

(Foroughi, Dilmaghani, and Famili 2008) Foroughi-Asl, A., S. Dilmaghani, and H. Famili. "Bond Strength of Reinforcement Steel in Self-Compacting Concrete." *International Journal of Civil Engineering*. (2008): Vol. 6: 1. 1 February 2013.

(Greenwald et al. 2006) Greenwald, Jeffrey, Donald L. Breeding, M. Doug Luttrell, Douglas H. Ross, Christopher C. Carter, and Eman Rouhani. "Self-Consolidating Grout Investigation: Compressive Strength, Shear Bond, Consolidation and Flow." *National Concrete Masonry Association*. (2006): 04-355. Web. 18 April 2011.

(Hodgson et al. 2004) Hodgson, Donald, Anton Schindler, Dan Brown, and Mary Stroup-Gardiner. "*The Feasibility of Using Self-Consolidating Concrete (SCC) in Dilled Shaft Applications*". Transportation Research Board. (2004). Web. 17 May 2011.

(Horta 2005) Horta, Alen. *Evaluation of Self-Consolidating Concrete for Bridge Structure Applications*. MS Thesis. Georgia Institute of Technology, Atlanta, (2005). Web. 17 May 2011.

(Huntzinger et al. 2009) Huntzinger, Deborah, John Gierke, Komar Kawatra, Timothy Eisele, and Lawrence Sutter. "Carbon Dioxide Sequestration in Cement Kiln Dust through Mineral Carbonation." *Environmental Science & Technology*. (2009): Vol. 43: 6. Web. 5 May 2011.

(IBC 2012) 2012 International Building Code. International Code Council, Illinois: 2011. Print.

(Kang and Kren 2007) Kang, Grace, and Alan Kren. "Structural Engineering Strategies Towards Sustainable Design." SEAONC Sustainable Design Committee. (2007). Web. 2 February 2013.

(Khayat 1999) Khayat, K.H. "Workability, Testing, and Performance of Self-Consolidating Concrete." *ACI Materials Journal*. (1999): 96-M43. Web. 18 April 2011.

(MSJC 2011) 2011 Building Code Requirements and Specification for Masonry Structures, Masonry Standards Joint Committee, Colorado: 2011. Print.

(Mwangi and Baltimore 2009) Mwangi, James, and Craig Baltimore. "Going Green in Concrete Masonry Construction by Use of Less Cement in Grout." *Masonry Chronicles*. (2009). Web. 20 April 2011.

(Rixom and Mailvaganam 1999) Rixom, Rodger, and Noel Mailvaganam. *Chemical Admixtures for Concrete*. New York: Routledge, 1999. Print.

(Ryan and Farnsworth 2003) Ryan, Robert, and Jennie Farnsworth. "*Self-Consolidating Grout: This Isn't Your Father's Grout Mix.*" Mason Contractors Association of America. (2003). Web. 2 February 2013.

(Wight and MacGregor 2009) Wight, James K., and James G. MacGregor. *Reinforced Concrete: Mechanics & Design*. 5th Ed. New Jersey: Pearson Education, Inc., 2009. Print.

(Worrell et al. 2001) Worrell, Ernst, Lynn Price, Nathan Martin, Chris Hendriks, and Leticia Ozawa Meida. "Carbon Dioxide Emissions from the Global Cement Industry." *Annual Review of Energy and the Environment*. (2001): Vol. 26: 303-329. Web. 14 April 2011.

American Society for Testing and Materials. ASTM Standards, ASTM International:

- A 615 *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*, 2012.
- C 90 *Standard Specification for Loadbearing Concrete Masonry Units*, 2011.
- C 143 *Standard Test Method for Slump of Hydraulic-Cement Concrete*, 2010.
- C 150 *Standard Specifications for Portland Cement*, 2012.
- C 157 *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*, 2008.
- C 270 *Standard Specification for Mortar for Unit Masonry*, 2012.
- C 404 *Standard Specification for Aggregates for Masonry Grout*, 2011.
- C 476 *Standard Specifications for Grout Masonry*, 2010.
- C 618 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, 2008.
- C 900 *Standard Test Method for Pullout Strength of Hardened Concrete*, 2012.
- C 989 *Standard Specification for Slag Cement for Use in Concrete and Mortars*, 2011.
- C 1019 *Standard Test Method for Sampling and Testing Grout*, 2011.
- C 1314 *Standard Test Method for Compressive Strength of Masonry Prisms*, 2011.
- C 1552 *Standard Practice for Capping Concrete Masonry Units, Related Units and Masonry Prisms for Compression Testing*, 2009.
- C 1611 *Standard Test Method of Slump Flow of Self-Consolidating Concrete*, 2009.

Appendices

Appendix A – Slump Flow Tests/Slump Tests

A.1 Slump Test Investigation of Conventional Grout

ASTM C 143 Test Report:
Standard Test Method for Slump of Hydraulic-Cement Concrete

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 100C
Conventional Grout: 0% Replacement of Portland Cement
*No Admixtures Used

Conventional Grout Proportions by Volume					
Type	Parts by volume of Portland Cement	Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
			Fine	Coarse	
100C	1	0	3 times the sum of the volumes of Portland Cement	2 times the sum of the volumes of Portland Cement	1.375 times the sum of the volumes of Portland Cement

Slump Test	
Test #	Slump (in.)
1	9.75
2	9.75
3	9.50
Average	9.75

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 50F
Experimental Grout: 50% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
50F	0.5	0.5	0	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	26.50	24.50	25.5	1	1.0
2	25.75	24.50	25.0	1	1.0
3	26.50	25.75	26.0	1	1.0

Average: 25.5 in.

* Slump flow = $(d_1 + d_2)/2$

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 60F
Experimental Grout: 60% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
60F	0.4	0.6	0	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	29.25	27.25	28.5	1	1.0
2	29.00	27.00	28.0	1	0.8
3	29.00	27.50	28.5	1	0.8

Average: 28.5 in.

* Slump flow = $(d_1 + d_2)/2$

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 70F
Experimental Grout: 70% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
70F	0.3	0.7	0	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	29.00	27.00	28.0	1	1.0
2	30.50	29.00	30.0	1	0.8
3	30.25	28.25	29.5	1	0.8

Average: 29.0 in.

* Slump flow = $(d_1 + d_2)/2$

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 60SF
Experimental Grout: 60% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
60SF	0.4	0.15	0.45	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	25.00	23.00	24.0	1	1.0
2	24.25	23.75	24.0	1	1.2
3	25.75	24.75	25.5	1	1.2

Average: 24.5 in.

* Slump flow = $(d_1 + d_2)/2$

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 70SF
Experimental Grout: 70% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
70SF	0.3	0.175	0.525	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	26.50	25.75	26.0	1	1.0
2	26.50	25.25	26.0	1	1.0
3	27.50	25.75	26.5	1	1.2

Average: 26.0 in.

* Slump flow = $(d_1 + d_2)/2$

A.2 Slump Flow Test Investigation of Experimental Grouts

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 7/13/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 80SF
Experimental Grout: 80% Replacement of Portland Cement
*No Admixtures Used

Experimental Grout Proportions by Volume							
Grout Mixture	Parts by Volume of Cementitious Material			Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition		Water
	Portland Cement	Type F Fly Ash	GGBFS		Fine	Coarse	
80SF	0.2	0.2	0.6	0	3 times the sum of the volumes of cementitious materials	2 times the sum of the volumes of cementitious materials	1.375 times the sum of the volumes of cementitious materials

Slump Flow Test					
Slump Flow Test #	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
1	26.00	27.50	27.0	1	1.0
2	27.00	26.00	26.5	1	1.2
3	27.75	27.00	27.5	1	1.2

Average: 27.0 in.

* Slump flow = $(d_1 + d_2)/2$

A.3 Slump Test for The Compression Experiment

ASTM C 143 Test Report:
Standard Test Method for Slump of Hydraulic-Cement Concrete

Date: 8/8/2012 Testing Lab: CAED Concrete Lab

Grout Test Type: 100C
Conventional Grout: 0% Replacement of Portland Cement
*No Admixtures Used
Grout Proportions by Volume as in Appendix A.1

Slump Test	
Type	Slump (in.)
100C	9.5

A.4 Slump Flow Tests for The Compression Experiment

ASTM C 1611 Test Report:
Standard Test Method for Slump Flow of Self-Consolidating Concrete
Filling Procedure B (Inverted Mold)

Date: 8/8/2012 Testing Lab: CAED Concrete Lab

*No Admixtures Used

Grout Proportions by Volume as in Appendix A.2
Portland Cement Replacement as in Table 2

Slump Flow Test					
Grout Mixture	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
50F	25.50	25.25	25.5	1	1.0
60F	29.50	27.50	28.5	1	1.0
70F	30.25	28.25	29.5	1	1.0
60SF	25.00	23.00	24.0	1	1.2
70SF	27.00	25.00	26.0	1	1.0
80SF	28.00	26.25	27.0	1	1.0

* Slump flow = $(d_1 + d_2)/2$

A.5 Slump Test for The Wall Experiment

ASTM C 143 Test Report:
Standard Test Method for Slump of Hydraulic-Cement Concrete

Date: See Table 4 Testing Lab: CAED Concrete Lab

Grout Test Type: 100C
Conventional Grout: 0% Replacement of Portland Cement
*No Admixtures Used
Grout Proportions by Volume as in Appendix A.1

Slump Test		
Grout Mixture	Grout Column ID	Slump (in.)
100C-C	3-1-1	10.00
100C-C	3-1-2	9.75
100C-C	3-1-3	9.75
100C-NC	3-2-1	9.75
100C-NC	3-2-2	9.75
100C-C	4-1-1	9.75
100C-NC	4-2-1	9.50

A.6 Slump Flow Tests for The Wall Experiment

ASTM C 1611 Test Report:

Standard Test Method for Slump Flow of Self-Consolidating Concrete

Filling Procedure B (Inverted Mold)

Date: See Table 4 Testing Lab: CAED Concrete Lab

*No Admixtures Used
Grout Proportions by Volume as in Appendix A.2
Portland Cement Replacement as in Table 2

Slump Flow Test						
Grout Mixture	Grout Column ID	Largest Diameter of Circular Spread of Grout, d_1, (in.)	Diameter Perpendicular to d_1, d_2, (in.)	Slump Flow, Average of d_1 and d_2 (in.)*	Visual Stability Index	T_{50}, (seconds)
50F	1-1-1	25.00	25.50	25.5	1	1.0
50F	1-1-2	25.75	26.50	26.0	1	0.8
60F	1-2-1	28.00	28.00	28.0	1	1.4
60F	1-2-2	29.25	27.75	28.5	1	0.8
70F	1-3-1	29.50	29.00	29.5	1	1.0
70F	1-3-2	28.75	28.25	28.5	1	1.0
60SF	2-1-1	24.00	24.00	24.0	1	1.6
60SF	2-1-2	26.00	24.00	25.0	1	1.0
70SF	2-2-1	26.50	26.00	26.5	1	0.8
70SF	2-2-2	26.50	25.00	26.0	1	1.0
80SF	2-3-1	27.25	26.00	27.0	1	1.2
80SF	2-3-2	27.50	26.00	27.0	1	1.2
50F	4-3-1	26.50	25.50	26.0	1	1.2
60F	4-4-1	28.75	27.50	28.0	1	0.8
70F	4-5-1	31.00	29.00	30.0	1	1.2
60SF	4-6-1	24.50	23.50	24.0	1	1.2
70SF	4-7-1	26.50	25.00	26.0	1	1.4
80SF	4-8-1	26.75	25.25	26.0	1	1.2

* Slump flow = $(d_1 + d_2)/2$

Appendix B – Grout Compressive Strengths from Compression Experiment

B.1 Compression Test Specimens: 7 Days of Curing

Testing Lab: CAED Concrete Lab

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 8/15/2012 Curing Time: 7 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating
100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	7	3 13/16	3 15/16	7 1/2	15.01	28000	1865	1.97	0.99	1848	1784
100C-2	7	4	4	7 9/16	16.00	29000	1813	1.89	0.97	1757	
100C-3	7	3 7/8	3 15/16	7 9/16	15.26	27000	1770	1.95	0.99	1746	
50F-1	7	3 3/4	3 15/16	7 9/16	14.77	8000	542	2.02	1.00	543	606
50F-2	7	3 15/16	4	7 1/2	15.75	9000	571	1.90	0.97	556	
50F-3	7	3 7/8	3 7/8	7 1/2	15.02	11000	733	1.94	0.98	719	
60F-1	7	3 15/16	3 15/16	7 1/2	15.50	7000	451	1.90	0.97	439	391
60F-2	7	3 3/4	3 15/16	7 7/16	14.77	5000	339	1.98	1.00	337	
60F-3	7	3 13/16	3 15/16	7 1/2	15.01	6000	400	1.97	0.99	396	
70F-1	7	3 5/8	3 11/16	7 7/16	13.37	3000	224	2.05	1.00	225	224
70F-2	7	3 5/8	3 11/16	7 7/16	13.37	3000	224	2.05	1.00	225	
70F-3	7	3 11/16	3 11/16	7 7/16	13.60	3000	221	2.02	1.00	221	
60SF-1	7	3 13/16	3 13/16	7 9/16	14.54	14000	963	1.98	1.00	959	944
60SF-2	7	3 3/4	3 13/16	7 1/2	14.30	13000	909	2.00	1.00	909	
60SF-3	7	3 7/8	3 15/16	7 1/2	15.26	15000	983	1.94	0.98	965	
70SF-1	7	3 15/16	3 15/16	7 1/2	15.50	16000	1032	1.90	0.97	1004	1062
70SF-2	7	3 15/16	4	7 1/2	15.75	17000	1079	1.90	0.97	1051	
70SF-3	7	3 15/16	3 15/16	7 1/2	15.50	18000	1161	1.90	0.97	1130	
80SF-1	7	3 13/16	3 15/16	7 1/2	15.01	15000	999	1.97	0.99	990	979
80SF-2	7	3 7/8	3 15/16	7 1/2	15.26	15000	983	1.94	0.98	965	
80SF-3	7	3 7/8	3 7/8	7 1/2	15.02	15000	999	1.94	0.98	981	

* Height to thickness correction factor from Table 1 of ASTM C 1314.
Values have been linearly interpolated as necessary

B.2 Compression Test Specimens: 14 Days of Curing

Testing Lab: CAED Concrete Lab ASTM C 1019 Test Report:

Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 8/22/2012 Curing Time: 14 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating

100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	14	3 13/16	3 15/16	7 1/2	15.01	32000	2132	1.97	0.99	2112	
100C-2	14	3 7/8	3 15/16	7 1/2	15.26	36000	2359	1.94	0.98	2317	2176
100C-3	14	3 7/8	4	7 9/16	15.50	33000	2129	1.95	0.99	2100	
50F-1	14	3 13/16	3 15/16	7 7/16	15.01	15000	999	1.95	0.99	985	
50F-2	14	3 7/8	3 15/16	7 7/16	15.26	15000	983	1.92	0.98	961	962
50F-3	14	3 13/16	3 7/8	7 1/2	14.77	14000	948	1.97	0.99	939	
60F-1	14	3 13/16	3 7/8	7 1/2	14.77	8000	542	1.97	0.99	537	
60F-2	14	3 13/16	3 13/16	7 1/2	14.54	8000	550	1.97	0.99	545	546
60F-3	14	3 3/4	3 13/16	7 7/16	14.30	8000	560	1.98	1.00	557	
70F-1	14	3 11/16	3 11/16	7 1/2	13.60	4000	294	2.03	1.00	295	
70F-2	14	3 5/8	3 3/4	7 5/16	13.59	4000	294	2.02	1.00	295	295
70F-3	14	3 5/8	3 3/4	7 7/16	13.59	4000	294	2.05	1.00	295	
60SF-1	14	3 13/16	3 7/8	7 9/16	14.77	21000	1421	1.98	1.00	1415	
60SF-2	14	3 7/8	3 7/8	7 5/8	15.02	22000	1465	1.97	0.99	1452	1404
60SF-3	14	3 7/8	3 15/16	7 7/16	15.26	21000	1376	1.92	0.98	1345	
70SF-1	14	3 13/16	4	7 1/2	15.25	24000	1574	1.97	0.99	1559	
70SF-2	14	3 7/8	3 15/16	7 1/2	15.26	24000	1573	1.94	0.98	1545	1535
70SF-3	14	3 13/16	3 13/16	7 1/2	14.54	22000	1514	1.97	0.99	1500	
80SF-1	14	3 15/16	3 15/16	7 1/2	15.50	22000	1419	1.90	0.97	1381	
80SF-2	14	3 13/16	3 7/8	7 7/16	14.77	22000	1489	1.95	0.99	1469	1409
80SF-3	14	3 3/4	3 7/8	7 1/2	14.53	20000	1376	2.00	1.00	1376	

* Height to thickness correction factor from Table 1 of ASTM C 1314.

Values have been linearly interpolated as necessary

B.3 Compression Test Specimens: 28 Days of Curing

Testing Lab: CAED Concrete Lab ASTM C 1019 Test Report:

Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 9/5/2012 Curing Time: 28 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating

100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	28	3 13/16	3 13/16	7 9/16	14.54	38000	2614	1.98	1.00	2602	2531
100C-2	28	3 15/16	3 15/16	7 9/16	15.50	37000	2386	1.92	0.98	2333	
100C-3	28	3 3/4	3 13/16	7 1/2	14.30	38000	2658	2.00	1.00	2658	
50F-1	28	3 13/16	3 7/8	7 7/16	14.77	19000	1286	1.95	0.99	1268	1278
50F-2	28	3 3/4	3 7/8	7 1/2	14.53	19000	1308	2.00	1.00	1308	
50F-3	28	3 3/4	3 13/16	7 1/2	14.30	18000	1259	2.00	1.00	1259	
60F-1	28	3 3/4	3 3/4	7 1/2	14.06	11000	782	2.00	1.00	782	715
60F-2	28	3 3/4	3 13/16	7 3/8	14.30	10000	699	1.97	0.99	693	
60F-3	28	3 13/16	3 7/8	7 1/2	14.77	10000	677	1.97	0.99	671	
70F-1	28	3 11/16	3 3/4	7 3/8	13.83	5000	362	2.00	1.00	362	398
70F-2	28	3 5/8	3 3/4	7 3/8	13.59	6000	441	2.03	1.00	443	
70F-3	28	3 9/16	3 5/8	7 3/8	12.91	5000	387	2.07	1.01	389	
60SF-1	28	3 7/8	3 7/8	7 9/16	15.02	25000	1665	1.95	0.99	1642	1659
60SF-2	28	3 13/16	3 7/8	7 9/16	14.77	25000	1692	1.98	1.00	1684	
60SF-3	28	3 13/16	3 15/16	7 1/2	15.01	25000	1665	1.97	0.99	1650	
70SF-1	28	3 13/16	3 15/16	7 1/2	15.01	29000	1932	1.97	0.99	1914	1900
70SF-2	28	3 13/16	3 7/8	7 1/2	14.77	28000	1895	1.97	0.99	1878	
70SF-3	28	3 13/16	3 13/16	7 1/2	14.54	28000	1926	1.97	0.99	1909	
80SF-1	28	3 13/16	3 7/8	7 1/2	14.77	27000	1828	1.97	0.99	1811	1722
80SF-2	28	3 13/16	4	7 7/16	15.25	28000	1836	1.95	0.99	1811	
80SF-3	28	3 7/8	3 15/16	7 1/2	15.26	24000	1573	1.94	0.98	1545	

* Height to thickness correction factor from Table 1 of ASTM C 1314.

Values have been linearly interpolated as necessary

B.4 Compression Test Specimens: 42 Days of Curing

Testing Lab: CAED Concrete Lab ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 9/19/2012 Curing Time: 42 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating
100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	42	3 7/8	4	7 1/2	15.50	45000	2903	1.94	0.98	2851	2995
100C-2	42	3 13/16	3 7/8	7 1/2	14.77	45000	3046	1.97	0.99	3018	
100C-3	42	3 3/4	3 15/16	7 1/2	14.77	46000	3115	2.00	1.00	3115	
50F-1	42	3 13/16	3 7/8	7 7/16	14.77	20000	1354	1.95	0.99	1335	1395
50F-2	42	3 7/8	3 15/16	7 1/2	15.26	21000	1376	1.94	0.98	1351	
50F-3	42	3 7/8	3 7/8	7 7/16	15.02	23000	1532	1.92	0.98	1497	
60F-1	42	3 11/16	3 7/8	7 1/2	14.29	12000	840	2.03	1.00	842	807
60F-2	42	3 3/4	3 3/4	7 7/16	14.06	11000	782	1.98	1.00	779	
60F-3	42	3 13/16	3 7/8	7 7/16	14.77	12000	812	1.95	0.99	801	
70F-1	42	3 11/16	3 3/4	7 1/2	13.83	6000	434	2.03	1.00	435	468
70F-2	42	3 5/8	3 11/16	7 7/16	13.37	6000	449	2.05	1.00	451	
70F-3	42	3 5/8	3 3/4	7 7/16	13.59	7000	515	2.05	1.00	517	
60SF-1	42	3 13/16	3 7/8	7 1/2	14.77	31000	2098	1.97	0.99	2079	2023
60SF-2	42	3 7/8	3 15/16	7 1/2	15.26	31000	2032	1.94	0.98	1995	
60SF-3	42	3 3/4	3 7/8	7 1/2	14.53	29000	1996	2.00	1.00	1996	
70SF-1	42	3 13/16	3 13/16	7 1/2	14.54	32000	2202	1.97	0.99	2181	2137
70SF-2	42	3 7/8	3 7/8	7 7/16	15.02	32000	2131	1.92	0.98	2083	
70SF-3	42	3 13/16	3 7/8	7 1/2	14.77	32000	2166	1.97	0.99	2146	
80SF-1	42	3 7/8	3 15/16	7 1/2	15.26	28000	1835	1.94	0.98	1802	1899
80SF-2	42	3 13/16	3 7/8	7 1/2	14.77	28000	1895	1.97	0.99	1878	
80SF-3	42	3 7/8	3 7/8	7 7/16	15.02	31000	2065	1.92	0.98	2018	

* Height to thickness correction factor from Table 1 of ASTM C 1314.
Values have been linearly interpolated as necessary

B.5 Compression Test Specimens: 56 Days of Curing

Testing Lab: CAED Concrete Lab ASTM C 1019 Test Report:

Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 10/3/2012 Curing Time: 56 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating

100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	56	3 13/16	3 13/16	7 1/2	14.54	47000	3234	1.97	0.99	3204	
100C-2	56	3 7/8	3 15/16	7 9/16	15.26	46000	3015	1.95	0.99	2974	3110
100C-3	56	3 13/16	3 7/8	7 1/2	14.77	47000	3181	1.97	0.99	3152	
50F-1	56	3 3/4	3 13/16	7 7/16	14.30	22000	1539	1.98	1.00	1532	
50F-2	56	3 7/8	3 7/8	7 7/16	15.02	23000	1532	1.92	0.98	1497	1552
50F-3	56	3 13/16	3 13/16	7 7/16	14.54	24000	1651	1.95	0.99	1628	
60F-1	56	3 5/8	3 3/4	7 1/2	13.59	12000	883	2.07	1.01	888	
60F-2	56	3 13/16	3 15/16	7 7/16	15.01	13000	866	1.95	0.99	854	884
60F-3	56	3 3/4	3 13/16	7 1/2	14.30	13000	909	2.00	1.00	909	
70F-1	56	3 9/16	3 5/8	7 7/16	12.91	7000	542	2.09	1.01	546	
70F-2	56	3 5/8	3 3/4	7 1/2	13.59	6000	441	2.07	1.01	444	495
70F-3	56	3 3/4	3 3/4	7 7/16	14.06	7000	498	1.98	1.00	495	
60SF-1	56	3 7/8	3 15/16	7 1/2	15.26	32000	2097	1.94	0.98	2059	
60SF-2	56	3 3/4	3 7/8	7 1/2	14.53	33000	2271	2.00	1.00	2271	2136
60SF-3	56	3 13/16	3 7/8	7 1/2	14.77	31000	2098	1.97	0.99	2079	
70SF-1	56	3 11/16	3 3/4	7 7/16	13.83	33000	2386	2.02	1.00	2390	
70SF-2	56	3 7/8	3 15/16	7 1/2	15.26	33000	2163	1.94	0.98	2124	2188
70SF-3	56	3 7/8	3 15/16	7 7/16	15.26	32000	2097	1.92	0.98	2050	
80SF-1	56	3 13/16	3 13/16	7 7/16	14.54	30000	2064	1.95	0.99	2036	
80SF-2	56	3 13/16	3 15/16	7 1/2	15.01	32000	2132	1.97	0.99	2112	2064
80SF-3	56	3 13/16	3 13/16	7 1/2	14.54	30000	2064	1.97	0.99	2045	

* Height to thickness correction factor from Table 1 of ASTM C 1314.
Values have been linearly interpolated as necessary

B.6 Compression Test Specimens: 130 Days of Curing

Testing Lab: CAED Concrete Lab ASTM C 1019 Test Report:

Standard Test Method for Sampling and Testing Grout

Project Identification: Compression Experiment, Grout Compression Tests

Grout Information

Grout Type: 100C, 50F, 60F, 70F, 60SF, 70SF, 80SF

Date Grouted: 8/8/2012

Date Tested: 12/16/2012 Curing Time: 130 Days

Grout Slumps: See Appendix A

Method of Consolidation: 50F, 60F, 70F, 60SF, 70SF, 80SF:Self-Consolidating

100C: Mechanical Vibration

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in^2)	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength (psi)	Avg. Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)								
100C-1	130	3 9/16	3 5/8	7 9/16	12.91	42000	3252	2.12	1.01	3284	3372
100C-2	130	3 5/8	3 5/8	7 9/16	13.14	44000	3348	2.09	1.01	3371	
100C-3	130	3 5/8	3 11/16	7 1/2	13.37	46000	3441	2.07	1.01	3460	
50F-1	130	3 5/8	3 5/8	7 1/2	13.14	22000	1674	2.07	1.01	1683	1712
50F-2	130	3 5/8	3 11/16	7 7/16	13.37	23000	1721	2.05	1.00	1728	
50F-3	130	3 5/8	3 11/16	7 3/8	13.37	23000	1721	2.03	1.00	1725	
60F-1	130	3 5/8	3 11/16	7 3/8	13.37	14000	1047	2.03	1.00	1050	1039
60F-2	130	3 5/8	3 11/16	7 7/16	13.37	15000	1122	2.05	1.00	1127	
60F-3	130	3 1/2	3 11/16	7 7/16	12.91	12000	930	2.13	1.01	939	
70F-1	130	3 3/8	3 9/16	7 7/16	12.02	7000	582	2.2	1.02	592	579
70F-2	130	3 1/2	3 1/2	7 7/16	12.25	7000	571	2.13	1.01	577	
70F-3	130	3 1/2	3 9/16	7 7/16	12.47	7000	561	2.13	1.01	567	
60SF-1	130	3 9/16	3 9/16	7 1/2	12.69	28000	2206	2.11	1.01	2225	2228
60SF-2	130	3 1/2	3 9/16	7 1/2	12.47	28000	2246	2.14	1.01	2271	
60SF-3	130	3 9/16	3 5/8	7 1/2	12.91	28000	2168	2.11	1.01	2186	
70SF-1	130	3 1/2	3 11/16	7 9/16	12.91	31000	2402	2.16	1.01	2433	2379
70SF-2	130	3 1/2	3 5/8	7 1/2	12.69	30000	2365	2.14	1.01	2392	
70SF-3	130	3 1/2	3 5/8	7 1/2	12.69	29000	2286	2.14	1.01	2312	
80SF-1	130	3 5/8	3 11/16	7 9/16	13.37	28000	2095	2.09	1.01	2109	2093
80SF-2	130	3 5/8	3 5/8	7 1/2	13.14	25000	1902	2.07	1.01	1913	
80SF-3	130	3 5/8	3 11/16	7 1/2	13.37	30000	2244	2.07	1.01	2257	

* Height to thickness correction factor from Table 1 of ASTM C 1314.

Values have been linearly interpolated as necessary

Appendix C – Grout Compressive Strengths from The Wall Experiment

C.1 Wall Compression Test Specimens: Wall 1

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (1-1-1) & (1-1-2)
Grout Type: 50F
Date Grouted: 7/27/2012
Date Tested: 12/4/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
1-1-1-1	130	3 11/16	3 3/4	7 5/8	13.83	24000	1736	2.07	1.01	1745
1-1-1-2	130	3 3/4	3 3/4	7 3/4	14.06	24000	1707	2.07	1.01	1716
1-1-1-3	130	3 11/16	3 3/4	7 11/16	13.83	22000	1591	2.08	1.01	1602
1-1-1-4	130	3 3/4	3 3/4	7 15/16	14.06	21000	1493	2.12	1.01	1507
1-1-1-5	130	3 5/8	3 3/4	7 5/8	13.59	21000	1545	2.10	1.01	1558
1-1-1-6	130	3 11/16	3 11/16	7 11/16	13.60	23000	1691	2.08	1.01	1703
1-1-2-1	130	3 11/16	3 11/16	7 3/4	13.60	14000	1030	2.10	1.01	1038
1-1-2-2	130	3 3/4	3 3/4	7 3/4	14.06	22000	1564	2.07	1.01	1573
1-1-2-3	130	3 13/16	3 13/16	7 5/8	14.54	23000	1582	2.00	1.00	1582
1-1-2-4	130	3 3/4	3 3/4	7 3/4	14.06	20000	1422	2.07	1.01	1430
1-1-2-5	130	3 5/8	3 3/4	7 3/4	13.59	20000	1471	2.14	1.01	1487
1-1-2-6	130	3 9/16	3 3/4	7 5/8	13.36	16000	1198	2.14	1.01	1211
								Average:		1513

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.1 Wall Compression Test Specimens: Wall 1

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (1-2-1) & (1-2-2)
Grout Type: 60F
Date Grouted: 7/27/2012
Date Tested: 12/4/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
1-2-1-1	130	3 5/8	3 11/16	7 13/16	13.37	15000	1122	2.16	1.01	1136
1-2-1-2	130	3 3/4	3 3/4	7 9/16	14.06	17000	1209	2.02	1.00	1211
1-2-1-3	130	3 3/4	3 3/4	7 11/16	14.06	17000	1209	2.05	1.00	1214
1-2-1-4	130	3 5/8	3 3/4	7 11/16	13.59	16000	1177	2.12	1.01	1188
1-2-1-5	130	3 3/4	3 3/4	7 3/4	14.06	16000	1138	2.07	1.01	1144
1-2-1-6	130	3 11/16	3 3/4	7 3/4	13.83	15000	1085	2.10	1.01	1094
1-2-2-1	130	3 5/8	3 3/4	7 13/16	13.59	13000	956	2.16	1.01	968
1-2-2-2	130	3 13/16	3 13/16	7 9/16	14.54	16000	1101	1.98	1.00	1096
1-2-2-3	130	3 3/4	3 3/4	7 11/16	14.06	18000	1280	2.05	1.00	1285
1-2-2-4	130	3 5/8	3 5/8	7 3/4	13.14	13000	989	2.14	1.01	1000
1-2-2-5	130	3 3/4	3 3/4	7 1/2	14.06	17000	1209	2.00	1.00	1209
1-2-2-6	130	3 3/4	3 3/4	7 13/16	14.06	15000	1067	2.08	1.01	1074
								Average:		1135

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.1 Wall Compression Test Specimens: Wall 1

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (1-3-1) & (1-3-2)
Grout Type: 70F
Date Grouted: 7/27/2012
Date Tested: 12/4/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
1-3-1-1	130	3 11/16	3 3/4	7 7/8	13.83	11000	795	2.14	1.01	804
1-3-1-2	130	3 11/16	3 3/4	7 5/8	13.83	12000	868	2.07	1.01	873
1-3-1-3	130	3 11/16	3 3/4	7 5/8	13.83	10000	723	2.07	1.01	727
1-3-1-4	130	3 5/8	3 5/8	7 3/4	13.14	10000	761	2.14	1.01	769
1-3-1-5	130	3 11/16	3 3/4	7 5/8	13.83	11000	795	2.07	1.01	800
1-3-1-6	130	3 5/8	3 3/4	7 13/16	13.59	12000	883	2.16	1.01	894
1-3-2-1	130	3 3/16	3 1/4	7 1/4	10.36	7000	676	2.27	1.02	691
1-3-2-2	130	3 5/8	3 3/4	7 3/4	13.59	13000	956	2.14	1.01	967
1-3-2-3	130	3 11/16	3 3/4	7 11/16	13.83	13000	940	2.08	1.01	946
1-3-2-4	130	3 11/16	3 3/4	7 3/4	13.83	11000	795	2.10	1.01	802
1-3-2-5	130	3 5/8	3 3/4	7 1/2	13.59	11000	809	2.07	1.01	814
1-3-2-6	130	3 9/16	3 3/4	7 7/8	13.36	12000	898	2.21	1.02	913
								Average:		833

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.2 Wall Compression Test Specimens: Wall 2

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (2-1-1) & (2-1-2)
Grout Type: 60SF
Date Grouted: 7/29/2012
Date Tested: 12/6/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
2-1-1-1	130	3 11/16	3 3/4	7 3/4	13.83	23000	1663	2.10	1.01	1677
2-1-1-2	130	3 11/16	3 13/16	7 13/16	14.06	33000	2347	2.12	1.01	2370
2-1-1-3	130	3 3/4	3 3/4	7 5/8	14.06	32000	2276	2.03	1.00	2282
2-1-1-4	130	3 3/4	3 3/4	7 11/16	14.06	31000	2204	2.05	1.00	2213
2-1-1-5	130	3 3/4	3 7/8	7 5/8	14.53	26000	1789	2.03	1.00	1794
2-1-1-6	130	3 3/4	3 3/4	7 7/8	14.06	25000	1778	2.10	1.01	1792
2-1-2-1	130	3 3/4	3 3/4	7 3/4	14.06	28000	1991	2.07	1.01	2002
2-1-2-2	130	3 13/16	3 7/8	7 3/4	14.77	38000	2572	2.03	1.00	2579
2-1-2-3	130	3 3/4	3 13/16	7 11/16	14.30	35000	2448	2.05	1.00	2458
2-1-2-4	130	3 3/4	3 3/4	7 3/4	14.06	36000	2560	2.07	1.01	2574
2-1-2-5	130	3 3/4	3 13/16	7 11/16	14.30	36000	2518	2.05	1.00	2528
2-1-2-6	130	3 5/8	3 11/16	7 7/8	13.37	36000	2693	2.17	1.01	2730
								Average:		2250

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.2 Wall Compression Test Specimens: Wall 2

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (2-2-1) & (2-2-2)
Grout Type: 70SF
Date Grouted: 7/29/2012
Date Tested: 12/6/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
2-2-1-1	130	3 11/16	3 3/4	7 3/4	13.83	25000	1808	2.10	1.01	1823
2-2-1-2	130	3 3/4	3 7/8	7 11/16	14.53	30000	2065	2.05	1.00	2073
2-2-1-3	130	3 3/4	3 3/4	7 3/4	14.06	28000	1991	2.07	1.01	2002
2-2-1-4	130	3 3/4	3 7/8	7 3/4	14.53	31000	2133	2.07	1.01	2145
2-2-1-5	130	3 11/16	3 3/4	7 5/8	13.83	27000	1953	2.07	1.01	1963
2-2-1-6	130	3 3/4	3 13/16	7 7/8	14.30	26000	1819	2.10	1.01	1833
2-2-2-1	130	3 3/4	3 3/4	7 13/16	14.06	28000	1991	2.08	1.01	2004
2-2-2-2	130	3 13/16	3 15/16	7 11/16	15.01	28000	1865	2.02	1.00	1868
2-2-2-3	130	3 3/4	3 13/16	7 3/4	14.30	28000	1958	2.07	1.01	1969
2-2-2-4	130	3 11/16	3 13/16	7 3/4	14.06	27000	1921	2.10	1.01	1936
2-2-2-5	130	3 3/4	3 13/16	7 9/16	14.30	27000	1889	2.02	1.00	1891
2-2-2-6	130	3 11/16	3 3/4	7 13/16	13.83	28000	2025	2.12	1.01	2044
								Average:		1963

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.2 Wall Compression Test Specimens: Wall 2

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (2-3-1) & (2-3-2)
Grout Type: 80SF
Date Grouted: 7/29/2012
Date Tested: 12/6/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.6
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
2-3-1-1	130	3 3/4	3 3/4	7 13/16	14.06	22000	1564	2.08	1.01	1575
2-3-1-2	130	3 3/4	3 13/16	7 3/4	14.30	25000	1749	2.07	1.01	1758
2-3-1-3	130	3 3/4	3 3/4	7 3/4	14.06	24000	1707	2.07	1.01	1716
2-3-1-4	130	3 3/4	3 13/16	7 11/16	14.30	24000	1679	2.05	1.00	1685
2-3-1-5	130	3 3/4	3 13/16	7 5/8	14.30	26000	1819	2.03	1.00	1823
2-3-1-6	130	3 3/4	3 7/8	7 11/16	14.53	27000	1858	2.05	1.00	1865
2-3-2-1	130	3 3/4	3 3/4	7 11/16	14.06	22000	1564	2.05	1.00	1571
2-3-2-2	130	3 13/16	3 13/16	7 13/16	14.54	24000	1651	2.05	1.00	1658
2-3-2-3	130	3 11/16	3 3/4	7 11/16	13.83	24000	1736	2.08	1.01	1747
2-3-2-4	130	3 3/4	3 3/4	7 3/4	14.06	27000	1920	2.07	1.01	1930
2-3-2-5	130	3 3/4	3 3/4	7 3/4	14.06	21000	1493	2.07	1.01	1501
2-3-2-6	130	3 11/16	3 3/4	7 5/8	13.83	22000	1591	2.07	1.01	1600
								Average:		1702

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.3 Wall Compression Test Specimens: Wall 3

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (3-1-2) & (3-1-3)
Grout Type: 100C-C
Date Grouted: 7/28/2012
Date Tested: 12/5/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.5
Method of Consolidation: Mechanical Vibrator

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
3-1-2-1	130	3 13/16	3 7/8	7 3/4	14.77	49000	3317	2.03	1.00	3325
3-1-2-2	130	3 11/16	3 3/4	7 13/16	13.83	35000	2531	2.12	1.01	2555
3-1-2-3	130	3 3/4	3 3/4	7 5/8	14.06	41000	2916	2.03	1.00	2923
3-1-2-4	130	3 3/4	3 13/16	7 11/16	14.30	41000	2868	2.05	1.00	2879
3-1-2-5	130	3 3/4	3 3/4	7 5/8	14.06	37000	2631	2.03	1.00	2638
3-1-2-6	130	3 3/4	3 3/4	7 11/16	14.06	43000	3058	2.05	1.00	3070
3-1-3-1	130	3 3/4	3 3/4	7 3/4	14.06	44000	3129	2.07	1.01	3146
3-1-3-2	130	3 13/16	3 7/8	7 5/8	14.77	41000	2775	2.00	1.00	2775
3-1-3-3	130	3 3/4	3 13/16	7 11/16	14.30	44000	3078	2.05	1.00	3090
3-1-3-4	130	3 3/4	3 3/4	7 11/16	14.06	39000	2773	2.05	1.00	2784
3-1-3-5	130	3 11/16	3 11/16	7 13/16	13.60	39000	2868	2.12	1.01	2895
3-1-3-6	130	3 3/4	3 13/16	7 11/16	14.30	43000	3008	2.05	1.00	3020
								Average:		2925

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

C.3 Wall Compression Test Specimens: Wall 3

ASTM C 1019 Test Report:
Standard Test Method for Sampling and Testing Grout

Testing Lab: CAED Concrete Lab
Project Identification: Wall Experiment, Grout Compression Tests

Grout Information:
Grout Columns ID: (3-2-1) & (3-2-2)
Grout Type: 100C-NC
Date Grouted: 7/28/2012
Date Tested: 12/5/2012 Curing Time: 130 Days
Grout Slumps: See Appendix A.5
Method of Consolidation: Self-Consolidating

Tested Grout Properties:

Grout Sample	Age at Test (Days)	Cross Section Dimensions		Avg. Height (in.)	Net Area (in.^{2})	Max Load (lb.)	Net Comp. Strength (psi)	h/t Ratio	h/t CF*	Corrected Net Strength, f_g (psi)
		Avg. Width (in.)	Avg. Length (in.)							
3-2-1-1	130	3 3/4	3 13/16	7 5/8	14.30	31000	2168	2.03	1.00	2174
3-2-1-2	130	3 5/8	3 11/16	7 5/8	13.37	31000	2319	2.10	1.01	2338
3-2-1-3	130	3 13/16	3 13/16	7 3/4	14.54	43000	2958	2.03	1.00	2966
3-2-1-4	130	3 3/4	3 3/4	7 11/16	14.06	38000	2702	2.05	1.00	2713
3-2-1-5	130	3 11/16	3 3/4	7 13/16	13.83	41000	2965	2.12	1.01	2993
3-2-1-6	130	3 3/4	3 13/16	7 11/16	14.30	40000	2798	2.05	1.00	2809
3-2-2-1	130	3 3/4	3 13/16	7 5/8	14.30	38000	2658	2.03	1.00	2665
3-2-2-2	130	3 3/4	3 13/16	7 11/16	14.30	38000	2658	2.05	1.00	2669
3-2-2-3	130	3 11/16	3 3/4	7 11/16	13.83	37000	2676	2.08	1.01	2694
3-2-2-4	130	3 3/4	3 13/16	7 3/4	14.30	41000	2868	2.07	1.01	2883
3-2-2-5	130	3 3/4	3 3/4	7 3/4	14.06	41000	2916	2.07	1.01	2931
3-2-2-6	130	3 3/4	3 13/16	7 11/16	14.30	44000	3078	2.05	1.00	3090
								Average:		2744

* Height to thickness correction factor from Table 1 of ASTM C 1314. Values have been linearly interpolated as necessary

Appendix D – Normalized and Averaged Compression Data from the Wall Experiment

D.1 Wall 1

D.1.1 Wall 1 Normalized Data

Wall Compression Test Specimens Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Values					
	50F	50F	60F	60F	70F	70F
	(1-1-1)	(1-1-2)	(1-2-1)	(1-2-2)	(1-3-1)	(1-3-2)
	NC	NC	NC	NC	NC	NC
132	0.99	0.71	1.05	1.03	1.54	1.58
108	0.91	0.87	1.10	1.16	1.38	1.41
84	0.88	0.84	1.14	0.96	1.33	1.39
60	0.94	0.92	1.17	1.24	1.26	1.63
36	1.00	0.92	1.17	1.05	1.51	1.67
12	1.02	0.61	1.09	0.93	1.39	1.19

D.1.2 Wall Compression Test Specimens: Identical Data Sets Combined and Nominalized

Identical Data Sets Combined: Averaged compressive strength of specimens with the same grout type and at the same height along the wall.

Identical Data Sets Combined from Appendix C.1

Identical Data Sets Combined			
Height from base, in.	Avg. Corrected Net Strength, f_g (psi)		
	50F	60F	70F
	NC	NC	NC
132	1457	1084	904
108	1523	1176	807
84	1469	1094	786
60	1592	1249	837
36	1644	1153	920
12	1391	1052	747
Average	1513	1135	833

Identical Data Sets Combined Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Averages		
	50F	60F	70F
	NC	NC	NC
132	0.85	1.04	1.56
108	0.89	1.13	1.39
84	0.86	1.05	1.36
60	0.93	1.20	1.45
36	0.96	1.11	1.59
12	0.81	1.01	1.29
Average	0.88	1.09	1.44

D.2 Wall 2

D.2.1 Wall 2 Normalized Data

Wall Compression Test Specimens Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Values					
	60SF	60SF	70SF	70SF	80SF	80SF
	(2-1-1)	(2-1-2)	(2-2-1)	(2-2-2)	(2-3-1)	(2-3-2)
	NC	NC	NC	NC	NC	NC
132	0.80	1.23	0.77	0.86	0.89	0.76
108	0.81	1.13	0.83	0.79	0.87	0.72
84	0.99	1.16	0.90	0.81	0.81	0.92
60	1.02	1.10	0.84	0.83	0.82	0.83
36	1.06	1.16	0.87	0.79	0.84	0.79
12	0.75	0.90	0.77	0.84	0.75	0.75

D.2.2 Wall Compression Test Specimens: Identical Data Sets Combined and Nominalized

<u>Identical Data Sets Combined</u>: Averaged compressive strength of specimens with the same grout type and at the same height along the wall.

Identical Data Sets Combined from Appendix C.2

Identical Data Sets Combined			
Height from base, in.	Avg. Corrected Net Strength, f_g (psi)		
	60SF	70SF	80SF
	NC	NC	NC
132	2261	1939	1733
108	2161	1927	1662
84	2393	2040	1808
60	2370	1985	1732
36	2474	1970	1708
12	1839	1914	1573
Average	2250	1963	1702

Identical Data Sets Combined Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Averages		
	60SF	70SF	80SF
	NC	NC	NC
132	1.01	0.81	0.83
108	0.97	0.81	0.79
84	1.07	0.86	0.86
60	1.06	0.83	0.83
36	1.11	0.83	0.82
12	0.83	0.80	0.75
Average	1.01	0.82	0.81

D.3 Wall 3

D.3.1 Wall 3 Normalized Data

Wall Compression Test Specimens Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Values			
	100C-C	100C-C	100C-NC	100C-NC
	(3-1-2)	(3-1-3)	(3-2-1)	(3-2-2)
	C	C	NC	NC
132	0.91	0.90	0.83	0.92
108	0.78	0.86	0.89	0.87
84	0.85	0.83	0.80	0.85
60	0.87	0.92	0.88	0.80
36	0.76	0.82	0.69	0.79
12	0.99	0.93	0.64	0.79

D.3.2 Wall Compression Test Specimens: Identical Data Sets Combined and Nominalized

Identical Data Sets Combined: Averaged compressive strength of specimens with the same grout type and at the same height along the wall.

Identical Data Sets Combined from Appendix C.3

Identical Data Sets Combined		
Height from base, in.	Avg. Corrected Net Strength, f_g (psi)	
	100C-C	100C-NC
	C	NC
132	3045	2949
108	2767	2962
84	2832	2798
60	3007	2830
36	2665	2503
12	3236	2420
Average	2925	2744

Identical Data Sets Combined Normalized to Average Corrected Net Strengths from Compression Experiment at Curing Time 130 Days: Appendix B.6

Height from base, in.	Normalized Averages	
	100C-C	100C-NC
	C	NC
132	0.90	0.87
108	0.82	0.88
84	0.84	0.83
60	0.89	0.84
36	0.79	0.74
12	0.96	0.72
Average	0.87	0.81

Appendix E – Consolidation Characteristics of Wall Compression Test Specimens

E.1 Top View of Wall Compression Specimens

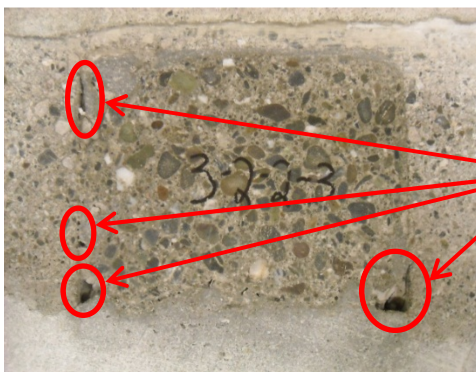
Below are pictures of the top view sections of wall compression test specimens before final cutting of 4"x4"x8" (nominal)

Descriptions next to pictures show how the specimens were visually classified in Appendix E.3

All specimens showed no evidence of segregation of aggregates

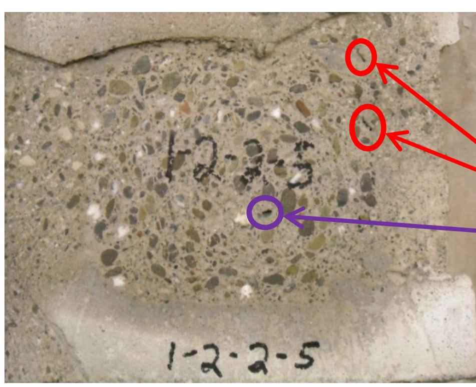
Top View of 2-1-1-3

No evidence of air voids



Top View of 3-2-2-3

1/16" to 1/2" mortar*



Top View of 1-2-2-5

1/16" mortar*
1/16" air void
Chipped**

*Air Voids located near the mortar fins

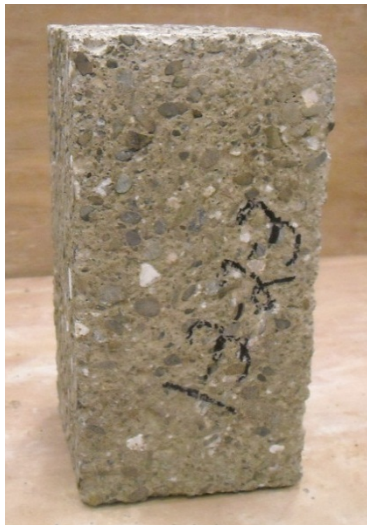
**Some aggregate chipped off during cutting due to its low strength

E.2 Side View of Wall Compression Specimens

Below are pictures of the side view sections of wall compression test specimens after final cutting of 4"x4"x8" (nominal)

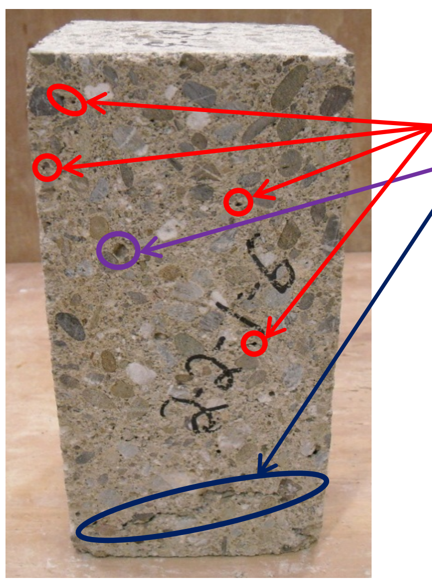
Descriptions next to pictures show how the specimens were visually classified in Appendix E.3

All specimens showed no evidence of segregation of aggregates



Side View of 1-3-2-3

No evidence of air voids
Chipped**



Side View of 2-2-1-6

1/16" air voids
1/8" air voids
1/16" crack*

*1/16" thick crack (void)

**Some aggregate chipped off during cutting due to its low strength

E.3 Recorded Visual Consolidation Characteristics of Wall Compression Specimens

E.3.1 Wall 1

Location on Specimen			
	1-1-1-6	1-1-2-6	1-2-1-6
Top:	1/16" mortar	1/16" mortar	Chipped, No evidence of air voids
Side:	No evidence of air voids	No evidence of air voids	Chipped, 1/4" air voids
	1-1-1-5	1-1-2-5	1-2-1-5
Top:	No evidence of air voids	1/16" mortar	Chipped, 1/16" mortar
Side:	1/16" crack, 1/16" air voids	1/16" - 1/8" air voids	Chipped, 1/8" air voids
	1-1-1-4	1-1-2-4	1-2-1-4
Top:	No evidence of air voids	1/16" mortar	Chipped, No evidence of air voids
Side:	1/16" crack, 1/16" air voids	1/16" - 1/8" air voids	Chipped, 1/16" air voids
	1-1-1-3	1-1-2-3	1-2-1-3
Top:	1/16" mortar	No evidence of air voids	Chipped, No evidence of air voids
Side:	1/8" crack, 1/16" air voids	1/16" air voids	Chipped
	1-1-1-2	1-1-2-2	1-2-1-2
Top:	No evidence of air voids	No evidence of air voids	Chipped, No evidence of air voids
Side:	1/16" air voids	1/16" - 1/8" air voids	Chipped, 1/16" air voids
	1-1-1-1	1-1-2-1	1-2-1-1
Top:	1/16" mortar	No evidence of air voids	Chipped, 1/16" mortar
Side:	1/16" air voids	1/16" - 1/4" air voids	Chipped, 1/16" - 1/8" air voids
	50F, 1-1-1, NC	**50F, 1-1-2, NC**	**60F, 1-2-1, NC**

Location on Specimen			
	1-2-2-6	1-3-1-6	1-3-2-6
Top:	Chipped, No evidence of air voids	Chipped, No evidence of air voids	Chipped, 1/16" mortar
Side:	Chipped, 1/16" air voids	Chipped, 1/16" air voids	Chipped, 1/16" air voids
	1-2-2-5	1-3-1-5	1-3-2-5
Top:	Chipped, 1/16" mortar, 1/16" air void	Chipped, No evidence of air voids	Chipped, No evidence of air voids
Side:	Chipped	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
	1-2-2-4	1-3-1-4	1-3-2-4
Top:	Chipped, No evidence of air voids	Chipped, No evidence of air voids	Chipped, 1/8" air void
Side:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids	Chipped, 1/16" air voids
	1-2-2-3	1-3-1-3	1-3-2-3
Top:	Chipped, No evidence of air voids	Chipped, No evidence of air voids	Chipped, No evidence of air voids
Side:	Chipped, 1/16" air voids	Chipped, 1/16" air voids	Chipped
	1-2-2-2	1-3-1-2	1-3-2-2
Top:	Chipped, No evidence of air voids	Chipped, No evidence of air voids	Chipped, No evidence of air voids
Side:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids	Chipped, 1/16" air voids
	1-2-2-1	1-3-1-1	1-3-2-1
Top:	Chipped, 1/8" - 1/2" mortar	Chipped, 1/8" mortar	Majorly Chipped, 1/8" mortar, 1/8" air voids
Side:	Chipped, 1/16" - 1/4" air voids	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" - 1/8" air voids
	60F, 1-2-2, NC	**70F, 1-3-1, NC**	**70F, 1-3-2, NC**

E.3 Recorded Visual Consolidation Characteristics of Wall Compression Specimens

E.3.2 Wall 2

Location on Specimen	60SF, 2-1-1, NC	60SF, 2-1-2, NC	70SF, 2-2-1, NC
	2-1-1-6	2-1-2-6	2-2-1-6
Top:	1" mortar	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" air voids	1/16" crack, 1/16" - 1/8" air voids
	2-1-1-5	2-1-2-5	2-2-1-5
Top:	No evidence of air voids	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" air voids	1/16" air voids
	2-1-1-4	2-1-2-4	2-2-1-4
Top:	No evidence of air voids	1/16" mortar	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	2-1-1-3	2-1-2-3	2-2-1-3
Top:	No evidence of air voids	1/16" mortar	No evidence of air voids
Side:	1/16" air voids	1/16" - 1/8" air voids	1/16" air voids
	2-1-1-2	2-1-2-2	2-2-1-2
Top:	No evidence of air voids	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	2-1-1-1	2-1-2-1	2-2-1-1
Top:	1/16" air voids	1/8" - 1/4" mortar	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" - 1/4" air voids	1/16" - 1/8" air voids

Location on Specimen	70SF, 2-2-2, NC	80SF, 2-3-1, NC	80SF, 2-3-2, NC
	2-2-2-6	2-3-1-6	2-3-2-6
Top:	No evidence of air voids	1/16" mortar	1/16" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	2-2-2-5	2-3-1-5	2-3-2-5
Top:	No evidence of air voids	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	2-2-2-4	2-3-1-4	2-3-2-4
Top:	1/8" air void	No evidence of air voids	No evidence of air voids
Side:	1/16" air voids	1/16" air voids	1/16" air voids
	2-2-2-3	2-3-1-3	2-3-2-3
Top:	No evidence of air voids	1/16" mortar	No evidence of air voids
Side:	1/16" air voids	1/16" - 1/8" air voids	1/16" air voids
	2-2-2-2	2-3-1-2	2-3-2-2
Top:	No evidence of air voids	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	2-2-2-1	2-3-1-1	2-3-2-1
Top:	1/16" air void	1/16" mortar	1/16" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids	1/16" air voids

E.3 Recorded Visual Consolidation Characteristics of Wall Compression Specimens

E.3.3 Wall 3

Location on Specimen	100C, 3-1-2, C	100C, 3-1-3, C
	3-1-2-6	3-1-3-6
Top:	1/16" mortar	No evidence of air voids
Side:	1/16" crack, 1/16" - 1/8" air voids	1/16" crack, 1/16" - 1/8" air voids
	3-1-2-5	3-1-3-5
Top:	1/16" mortar	No evidence of air voids
Side:	1/8" crack, 1/16" air voids	1/16" - 1/8" air voids
	3-1-2-4	3-1-3-4
Top:	No evidence of air voids	No evidence of air voids
Side:	1/16" crack, 1/16" air voids	1/16" crack, 1/16" - 1/8" air voids
	3-1-2-3	3-1-3-3
Top:	1/16" mortar	No evidence of air voids
Side:	1/16" air voids	1/16" - 1/8" air voids
	3-1-2-2	3-1-3-2
Top:	No evidence of air voids	No evidence of air voids
Side:	1/16" - 1/4" air voids	1/16" - 1/8" air voids
	3-1-2-1	3-1-3-1
Top:	No evidence of air voids	No evidence of air voids
Side:	1/8" air voids	1/16" - 1/8" air voids

Location on Specimen	100C, 3-2-1, NC	100C, 3-2-2, NC
	3-2-1-6	3-2-2-6
Top:	1/4"mortar	1/16" mortar
Side:	1/16" - 1/4" air voids	1/16" - 1/8" air voids
	3-2-1-5	3-2-2-5
Top:	No evidence of air voids	1/16" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	3-2-1-4	3-2-2-4
Top:	No evidence of air voids	1/16" - 1/4" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	3-2-1-3	3-2-2-3
Top:	1/16" mortar	1/16" - 1/2" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/8" air voids
	3-2-1-2	3-2-2-2
Top:	No evidence of air voids	1/8" mortar
Side:	1/16" - 1/8" air voids	1/16" crack, 1/16" - 1/8" air voids
	3-2-1-1	3-2-2-1
Top:	1/4" mortar	1/8" mortar
Side:	1/16" - 1/8" air voids	1/16" - 1/4" air voids

Appendix F – Consolidation Characteristics of Reinforcement Sections

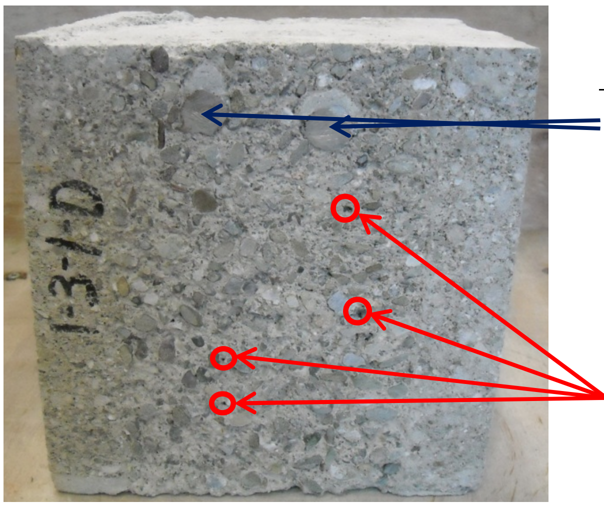
F.1 Pictures of Cross Sections through Reinforcement Layers

Below are pictures of the vertical cuts across the mid-section of the grout columns at the reinforcement layers.

Descriptions next to pictures show how the specimens were visually classified in Appendix F.2

Consolidation grades are determined by diameter of air void size, following Table 5.

All specimens showed no evidence of segregation of aggregates



Cross Section of 1-3-1-D

Reinforcement

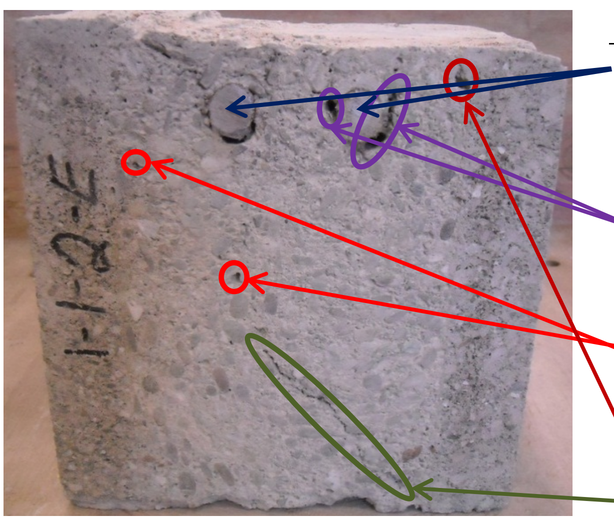
Next to Reinforcement

No evidence of air voids

Cross Section

Chipped*

1/16" air voids



Cross Section of 1-1-2-E

Reinforcement

Next to Reinforcement

1/8" air void***

Cross Section

1/16" air voids

1/8" air voids

1/16" crack**

*Some aggregate chipped off during cutting due to its low strength

**1/16" thick crack (void)

***Largest air void next to reinforcement of section is 1/8"

F.2 Recorded Visual Consolidation Characteristics of Cross Section through Reinforcement Layers

F.2.1 Wall 1

F.2.1.1 Mixture 50F

	1-1-1-F	1-1-2-F
Consolidation Grade:	2	1
Cross Section:	1/8" crack, 1/16" - 1/8" air voids	1/16" air voids
Next to Reinforcement:	1/8" air void	No evidence of air voids
	1-1-1-E	1-1-2-E
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" crack, 1/16" - 1/8" air voids
Next to Reinforcement:	1/16" air void	1/8" air void
	1-1-1-D	1-1-2-D
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16" air voids
Next to Reinforcement:	1/16" air void	1/8" air void
	1-1-1-C	1-1-2-C
Consolidation Grade:	2	2
Cross Section:	1/16" crack, 1/16" - 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	1-1-1-B	1-1-2-B
Consolidation Grade:	2	2
Cross Section:	1/16" crack, 1/16" - 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	1-1-1-A	1-1-2-A
Consolidation Grade:	5	2
Cross Section:	1/16" - 3/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	50F, 1-1-1, NC	**50F, 1-1-2, NC**

<u>Average Grout Consolidation Grade</u>: <u>**2.2**</u>

F.2.1.2 Mixture 60F

	60F, 1-2-1, NC	60F, 1-2-2, NC
	1-2-1-F	1-2-2-F
Consolidation Grade:	2	5
Cross Section:	Chipped, 1/16" air voids	Chipped, 1/16" - 1" air voids
Next to Reinforcement:	1/8" air void	1/4" air void
	1-2-1-E	1-2-2-E
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	1-2-1-D	1-2-2-D
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/8" air void	1/4" air void
	1-2-1-C	1-2-2-C
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/4" air void	1/8" air void
	1-2-1-B	1-2-2-B
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	1-2-1-A	1-2-2-A
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" - 1/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void

Average Grout Consolidation Grade: **2.3**

F2.1.3 Mixture 70F

	70F, 1-3-1, NC	70F, 1-3-2, NC
	1-3-1-F	1-3-2-F
Consolidation Grade:	2	1
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/8" air void	No evidence of air voids
	1-3-1-E	1-3-2-E
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	1-3-1-D	1-3-2-D
Consolidation Grade:	1	2
Cross Section:	Chipped, 1/16" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	No evidence of air voids	1/16" air void
	1-3-1-C	1-3-2-C
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" air voids	Chipped, 1/16" - 1/8" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	1-3-1-B	1-3-2-B
Consolidation Grade:	2	2
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/16" air void	1/8" air void
	1-3-1-A	1-3-2-A
Consolidation Grade:	2	1
Cross Section:	Chipped, 1/16" - 1/8" air voids	Chipped, 1/16" air voids
Next to Reinforcement:	1/4" air void	No evidence of air voids

Average Grout Consolidation Grade: **1.8**

F.2.2 Wall 2

F2.2.1 Mixture 60SF

	60SF, 2-1-1, NC	60SF, 2-1-2, NC
	2-1-1-F	2-1-2-F
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" - 1/4" air voids
Next to Reinforcement:	1/16" air void	1/4" air void
	2-1-1-E	2-1-2-E
Consolidation Grade:	1	2
Cross Section:	1/16" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	No evidence of air voids	1/8" air void
	2-1-1-D	2-1-2-D
Consolidation Grade:	2	2
Cross Section:	1/16" - 1/4" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/4" air void	1/4" air void
	2-1-1-C	2-1-2-C
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/4" air void	1/8" air void
	2-1-1-B	2-1-2-B
Consolidation Grade:	4	2
Cross Section:	1/16"- 1/8" air voids	1/16" crack, 1/16" - 1/8" air voids
Next to Reinforcement:	3/4" air void	1/16" air void
	2-1-1-A	2-1-2-A
Consolidation Grade:	2	2
Cross Section:	1/16" - 3/8" holes	1/16"- 1/8" air voids
Next to Reinforcement:	No evidence of air voids	1/16" air void

Average Grout Consolidation Grade: **2.1**

F.2.2.2 Mixture 70SF

	70SF, 2-2-1, NC	70SF, 2-2-2, NC
	2-2-1-F	2-2-2-F
Consolidation Grade:	2	2
Cross Section:	1/16" - 1/4" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/4" air void	1/4" air void
	2-2-1-E	2-2-2-E
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/16" air void	1/8" air void
	2-2-1-D	2-2-2-D
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16" air voids
Next to Reinforcement:	1/8" air void	1/16" air void
	2-2-1-C	2-2-2-C
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/16" air void	1/8" air void
	2-2-1-B	2-2-2-B
Consolidation Grade:	2	1
Cross Section:	1/16" air voids	1/16" air voids
Next to Reinforcement:	1/16" air void	No evidence of air voids
	2-2-1-A	2-2-2-A
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/16" air void

Average Grout Consolidation Grade: **1.9**

F.2.2.3 Mixture 80SF

	80SF, 2-3-1, NC	80SF, 2-3-2, NC
	2-3-1-F	2-3-2-F
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" air voids
Next to Reinforcement:	1/4" air void	1/16" air void
	2-3-1-5	2-3-2-E
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	2-3-1-D	2-3-2-D
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" air voids
Next to Reinforcement:	1/4" air void	1/8" air void
	2-3-1-C	2-3-2-C
Consolidation Grade:	4	2
Cross Section:	1/16" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1" air void	1/8" air void
	2-3-1-B	2-3-2-B
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16"- 3/8" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	2-3-1-A	2-3-2-A
Consolidation Grade:	1	4
Cross Section:	1/16"- 1/8" air voids	1/16" air voids
Next to Reinforcement:	No evidence of air voids	3/4" air void

Average Grout Consolidation Grade: **2.3**

F.2.3 Wall 3

F.2.3.1 Mixture 100C - C

	3-1-2-F	3-1-3-F
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/16" air void
	3-1-2-E	3-1-3-E
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" air voids
Next to Reinforcement:	1/8" air void	1/8" air void
	3-1-2-D	3-1-3-D
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/8" air void	1/16" air void
	3-1-2-C	3-1-3-C
Consolidation Grade:	1	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	No evidence of air voids	1/16" air void
	3-1-2-B	3-1-3-B
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	3-1-2-A	3-1-3-A
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" air voids
Next to Reinforcement:	1/8" air void	1/16" air void
	100C, 3-1-2, C	**100C, 3-1-3, C**

Average Grout Consolidation Grade: **2.0**

F.2.3.2 Mixture 100C - NC

	100C, 3-2-1, NC	100C, 3-2-2, NC
	3-2-1-F	3-2-2-F
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" crack, 1/16" - 3/8" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	3-2-1-E	3-2-2-E
Consolidation Grade:	2	2
Cross Section:	1/16"- 1/8" air voids	1/16" crack, 1/16" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	3-2-1-D	3-2-2-D
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16" crack, 1/4" - 1/16" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	3-2-1-C	3-2-2-C
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16" air voids
Next to Reinforcement:	1/16" air void	1/16" air void
	3-2-1-B	3-2-2-B
Consolidation Grade:	1	2
Cross Section:	1/16" air voids	1/16"- 1/8" air voids
Next to Reinforcement:	No evidence of air voids	1/16" air void
	3-2-1-A	3-2-2-A
Consolidation Grade:	2	2
Cross Section:	1/16" air voids	1/16" air voids
Next to Reinforcement:	1/16" air void	1/16" air void

Average Grout Consolidation Grade: **1.9**

Appendix G – Rebar Pullout Investigation

G.1 Bond Strength of Grouts: Wall 4

ASTM C 900 Test Report:
Standard Test Method for Pullout Strength of Hardened Concrete

Project Identification: Wall Experiment, Rebar Pullout Tests
Testing Lab: CAED High Bay Laboratory
Date Tested: 1/16/2013

Pullout Sample	Age at Test (Days)	Nominal Reinforcement diameter, d_b (in.)	Embedment Length, l (in.)	Ultimate Axial Force, T (lb.)	Bond Strength, τ (psi)	Avg. Bond Strength, τ (psi)
4-1-1-1	168	3/8	15 11/16	10175	551	
4-1-1-2	168	3/8	15 3/4	10125	546	548
4-1-1-3	168	3/8	15 11/16	10150	549	
4-2-1-1	168	3/8	15 3/4	7900	426	
4-2-1-2	168	3/8	15 3/4	7850	423	425
4-2-1-3	168	3/8	15 3/4	7900	426	
4-3-1-1	170	3/8	15 3/4	10850	585	
4-3-1-2	170	3/8	15 3/4	10650	574	571
4-3-1-3	170	3/8	15 5/8	10225	555	
4-4-1-1	170	3/8	15 3/4	7625	411	
4-4-1-2	170	3/8	15 13/16	7575	407	401
4-4-1-3	170	3/8	15 11/16	7125	386	
4-5-1-1	170	3/8	15 3/4	7750	418	
4-5-1-2	170	3/8	15 11/16	7525	407	409
4-5-1-3	170	3/8	15 1/2	7350	403	
4-6-1-1	170	3/8	15 1/2	10900	597	
4-6-1-2	170	3/8	15 11/16	10850	587	589
4-6-1-3	170	3/8	15 11/16	10800	584	
4-7-1-1	170	3/8	15 3/4	9700	523	
4-7-1-2	170	3/8	15 13/16	9600	515	524
4-7-1-3	170	3/8	15 1/2	9750	534	
4-8-1-1	170	3/8	15 3/4	10125	546	
4-8-1-2	170	3/8	15 3/4	10150	547	548
4-8-1-3	170	3/8	15 9/16	10100	551	

G.2 Normalized Data for Bond Strengths

Average Bond Strength Per Mixture was Normalized to the Square Root of the Average Corrected Net Strengths x 12.043, from the Wall Experiment at Curing Time 130 Days: Appendix D

Grout Mixture	Avg. Bond Strength, τ (psi)	Average Net Corrected Compressive Strength of Wall Experiment, f_g (psi)	12.043* SQRT(f_g) (psi)	Normalized Values*
100C-C	548	2925	651.3	0.84
100C-NC	425	2744	630.9	0.67
50F	571	1513	468.4	1.22
60F	401	1135	405.7	0.99
70F	409	833	347.6	1.18
60SF	589	2250	571.2	1.03
70SF	524	1963	533.6	0.98
80SF	548	1702	496.8	1.10

*Normalized Values = $\frac{\tau}{12.043\sqrt{f_g}}$ [psi / psi]

G.3 Required Development Length of Reinforcement

Modified rebar development length equation (Eq.4) : $$l_d = \frac{0.13 d_b^2 (\frac{T}{A_s})\gamma}{K\sqrt{f_g}}$$

Average compressive strength of grouts from The Compression Experiment, f_g (Appendix B) :

100C : f_g taken after 28 days of curing
50F, 60F, 70F, 60SF, 70SF, 80SF : f_g taken after 56 days of curing

Nominal diameter of reinforcement, d_b = 0.375 in.

Effective cross-sectional area of reinforcement, A_s= 0.11 in.^{2}

K, shall not exceed the smallest of :

min. masonry clear cover : Shown in table below
5 d_b = 1.875 in.

Reinforcement size factor, γ = 1.0

Grout Mixture	Sample	Min. Masonry Clear Cover (in.)	Average Comp. Strength, f_g (psi)	Tensile Axial Force, T (lb)	Req. Development Length of Reinforcement Bars, l_d (in.)
100C -C	4-1-1-1	2.94	2531	10175	17.85
100C -C	4-1-1-2	3.31	2531	10125	17.77
100C -C	4-1-1-3	3.25	2531	10150	17.81
100C -NC	4-2-1-1	3.31	2531	7900	13.86
100C -NC	4-2-1-2	3.13	2531	7850	13.77
100C -NC	4-2-1-3	3.00	2531	7900	13.86
50F	4-3-1-1	3.19	1552	10850	24.31
50F	4-3-1-2	3.13	1552	10650	23.86
50F	4-3-1-3	3.06	1552	10225	22.91
60F	4-4-1-1	2.75	884	7625	22.64
60F	4-4-1-2	2.63	884	7575	22.50
60F	4-4-1-3	2.56	884	7125	21.16
70F	4-5-1-1	3.25	495	7750	30.75
70F	4-5-1-2	2.81	495	7525	29.86
70F	4-5-1-3	3.06	495	7350	29.16
60SF	4-6-1-1	3.25	2136	10900	20.82
60SF	4-6-1-2	2.56	2136	10850	20.72
60SF	4-6-1-3	3.19	2136	10800	20.63
70SF	4-7-1-1	2.06	2188	9700	18.31
70SF	4-7-1-2	1.88	2188	9600	18.12
70SF	4-7-1-3	2.63	2188	9750	18.40
80SF	4-8-1-1	3.06	2064	10125	19.67
80SF	4-8-1-2	2.88	2064	10150	19.72
80SF	4-8-1-3	3.31	2064	10100	19.62

G.4 Normalized Data for Development Length of Reinforcement

The required theoretical development lengths of reinforcements, l_d,
were normalized to the actual embedment lengths, l, of the rebar pullout specimens

Grout Mixture	Sample	Embedment Length, l (in.)	Req. Development Length of Reinforcement Bars, l_d (in.)	Normalized Values*	Average Normalized Values per Mixture
100C -C	4-1-1-1	15.69	17.85	1.14	1.13
100C -C	4-1-1-2	15.75	17.77	1.13	
100C -C	4-1-1-3	15.69	17.81	1.14	
100C -NC	4-2-1-1	15.75	13.86	0.88	0.88
100C -NC	4-2-1-2	15.75	13.77	0.87	
100C -NC	4-2-1-3	15.75	13.86	0.88	
50F	4-3-1-1	15.75	24.31	1.54	1.51
50F	4-3-1-2	15.75	23.86	1.52	
50F	4-3-1-3	15.63	22.91	1.47	
60F	4-4-1-1	15.75	22.64	1.44	1.40
60F	4-4-1-2	15.81	22.50	1.42	
60F	4-4-1-3	15.69	21.16	1.35	
70F	4-5-1-1	15.75	30.75	1.95	1.91
70F	4-5-1-2	15.69	29.86	1.90	
70F	4-5-1-3	15.50	29.16	1.88	
60SF	4-6-1-1	15.50	20.82	1.34	1.33
60SF	4-6-1-2	15.69	20.72	1.32	
60SF	4-6-1-3	15.69	20.63	1.31	
70SF	4-7-1-1	15.75	18.31	1.16	1.17
70SF	4-7-1-2	15.81	18.12	1.15	
70SF	4-7-1-3	15.50	18.40	1.19	
80SF	4-8-1-1	15.75	19.67	1.25	1.25
80SF	4-8-1-2	15.75	19.72	1.25	
80SF	4-8-1-3	15.56	19.62	1.26	

*Normalized Values = $\frac{l_d}{l}$ [in. / in.]

Appendix H – Metric Conversions

Quantity	U.S. Customary Units	Metric Units	Multiply*
Length	ft.	m	0.3048
	ft.	mm	304.8
	in.	mm	25.4
Area	yd^2	m^2	0.83612736
	$ft.^2$	m^2	0.09290304
	$in.^2$	mm^2	645.16
Volume	yd^3	m^3	0.764555
	$ft.^3$	m^3	0.0283168
	$in.^3$	mm^3	16,387.06
Mass density	pcf	kg/m^3	16.0185
Force	lb-force	N	4.44822
	kip (1,000 lb-force)	kN	4.44822
Force/unit length	lb/ft	N/m	14.5939
	kip/ft	kN/m	14.5939
Force/unit area	psf	Pa (N/m^2)	47.8803
	psi	MPa	0.00689476
	ksi	MPa	6.89476

*Multiply U.S. customary units by given number to convert into metric units