No Admixture, Sustainable, Self-Consolidating Grout

Baltimore, Craig, Ph.D., S.E.[1], Mwangi, James P., Ph.D., S.E.[2], and Bateman, Eric W.[3]

ABSTRACT: The consolidation of grout in concrete masonry unit (CMU) walls is labor-intensive. Also, the grout's Portland cement content has a high embodied energy demand – a non-sustainable characteristic. For the labor-intensive issue, chemical admixture self-consolidating grouts have been used in walls 12.67 ft. (3.86 m) tall, however the chemical additive can impose new limitations on the grout (non-robust characteristics). No admixture self-consolidating grout with high percentage Portland cement replacement have potential for robust and sustainable application.

This paper reports on the consolidation of no admixture self-consolidating grout made by substituting high percentages of Portland cement with Type-F fly ash and/or GGBFS. The percent replacement ranged from 50% to 80% by volume.

Single lift test CMU walls were 12.67 ft. (3.86 m) tall. The relative reinforcement consolidation was assessed by comparison to traditional mechanically consolidated grout and also compared to criteria of ACI technical notes for shotcrete. Cure time was 125 days.

Keywords: Self-Consolidating Grout, Conventional Grout, Sustainable, Portland cement, Fly Ash, Blast Furnace, Slag.

NOTATION

ACI	American Concrete Institute
ASTM	American Society of Testing and Materials
CMU	Concrete Masonry Unit
GGBFS	Ground Granulated Blast Furnace Slag
T_{50}	Relative Viscosity of Self Consolidating Concrete (per ASTM 1611)
TMS	The Masonry Society
VSI	Visual Stability Index (per ASTM 1611)

1) Professor, California Polytechnic State University – San Luis Obispo, California, USA, Architectural Eng. Dept., cbaltimo@calpoly.edu
2) Professor, California Polytechnic State University – San Luis Obispo, California, USA, Architectural Eng. Dept., jmwangi@calpoly.edu
3) Graduate Student, California Polytechnic State University – San Luis Obispo, California, 93407, Arch. Eng. Dept., ebateman@calpoly.edu

1 INTRODUCTION

This paper reports on an investigation of no chemical admixture self-consolidating grout. The no chemical admixture self-consolidating grout investigation consists of using a traditional grout mix design and replacing a high percentage of the Portland cement with Type F fly ash and/or ground granulated blast furnace slag (GGBFS). No other modifications were made to the mix design. No chemical admixtures were added to the mix design. In this particular investigation, the parameter of material proportions (as measured by volume) was kept constant. The material proportions were cemetitious, fine aggregate, course aggregate, and water. Thus, the actual water to cement ratio was significantly increased due to the high percentage replacement of Portland cement; but the water to cemetitious material ratio was kept constant.

By using fly ash and GGBFS to replace a significant portion of the Portland cement, a sustainable benefit was also realized. The benefit was in lowering the embodied energy demand and in extending the life of our landfills. The embodied energy benefit occurs by decreasing or limiting the Portland cement required in a grout mix design. This would in turn lower the demand for Portland cement and thus lower the need to produce and ship the Portland cement. The extending of a landfill life occurs by using a waste product – fly ash and GGBFS – instead of disposing of the waste product.

Fly ash and GGBFS are waste materials and as waste products have no embodied energy. Currently, much of the embodied energy in Portland cement production is produce through fossil fuels (e.g. heating limestone kilns and transportation). By recycling the waste products through Portland cement replacement a cleaner and more sustainable grout is created by decreasing embodied energy of production [1].

In high seismic regions, structural designs typically require fully grouted walls with significant reinforcement. The volume of grout in a fully grouted 8x8x16 in. (203x203x406 mm) concrete masonry unit (CMU) is approximately fifty two percent of the total volume - over half the volume of a fully grouted masonry wall is grout. Even in a partially grouted wall, the volume of grout would be large enough to realize the benefit from high percentage replacement of Portland cement.

The particle size and shape of fly ash is spherical. The spherical shape acts like little ball bearings in the mix and increases fluidity without adding additional water [2]. With a high percentage of Portland cement replacement with fly ash, the increase in fluidity is sufficient to change the behavior of the grout mix from slump and placement to flow and self-consolidation. Self-consolidating grout is a highly flowable grout that can spread into place under its own weight and achieve consolidation with no air pockets; limited segregation of the aggregate matrix; and provide bond between the concrete masonry unit, grout, and reinforcement [3].

Self-consolidating grout in concrete masonry construction also has important economic benefits. In traditional grout placement, each lift needs to be mechanically consolidated (vibrated) and reconsolidated before the next lift is placed to ensure minimum voids and proper reinforcement bonding. Mechanical consolidation is a time and energy consuming operation. Self-consolidating grout eliminates the need for mechanical equipment thus saving time and therefore reducing labor costs [4], [5].

The high percent replacement of Portland cement has the sustainable benefit of lowering embodied energy and making use of a waste material; and has the physical behavior benefit of becoming a self-consolidating grout. However, the higher water to cement ratio would lead to a lower strength. While this is true initially, the pozzolanic reaction of the fly ash and GGBFS adds strength over time. Proper construction sequencing and scheduling may accommodate a lower initial strength (i.e. 28 day) and allow for the required strength at later time (e.g 120 day).

As an initial step to confirm the self consolidation properties of high percent replacement Portland cement in a traditional grout mix design, a test program was set-up and conducted. The test results indicate the strong potential exists.

2 TEST PROGRAM

The test program had two phases or parts; in-place testing and grout mold testing. The grout mold testing was used as a base-line for compression strength and conformed to ASTM C 1019 standards. The in-place testing consisted of constructing four professionally built walls. Coupons were cut from the walls for visual inspection and testing.

The grout molds were made and tested in accordance with ASTM C1019, with one exception: the grout was placed into the cores of 8x8x16 in. (203x203x406 mm) nominal CMU rather than constructing a grout mold using four CMUs. This exception was made due to limits space and to mimic the same water absorption characteristics the grout experiences while curing in the core of the CMU, yet still providing the absorptive mold requirement in ASTM C1019. The grouted CMUs were dry cured, complying with ASTM C157, as seen in Figure 1.

(a) (b)

Figure 1. (a) Placing Grout into Cores of CMUs and (b) Dry Curing Grout Specimens

The four walls for in-place testing were constructed by professional masons - 12.67 ft (3.86 m) in height. All the walls were built in running bond pattern using double square core 8x8x16 in. (203x203x406 mm) nominal CMU. The walls were single wythe and 19 courses in height. Full mortar bedding was used to prevent the grout from flowing into adjacent grout columns (Figure 2a). 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 consolidation - 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 reinforcement and grouts at varying heights along the wall. Walls 1, 2, and 3 were 4.0 ft. (1.2 m) nominal wide and consisted of six grout columns. The walls had two #5 (16 mm) horizontal reinforcement bars placed at 2.0 ft. (0.61 m) on center vertically [Figure 2a]. Wall 4 was 5.33 ft (1.63 m) nominal wide and consisted of eight grout columns [Figure 3a]. Each grout column had one #3 (10 mm) vertical reinforcing bar centered in the core and extended throughout the entire height of the column [Figure 2b]. Cleanouts were provided in the first course of all grout columns [Figure 3b].

(a) (b)

Figure 2. Wall Construction (a) Horizonal Steel Location and (b) Vertical Steel Location

(a) (b)

Figure 3. (a) Wall Elevation and (b) Location of Cleanouts

Materials used were [7]:

- Portland cement Type II-IV complying with ASTM C150
- Coal fly ash Class F complying to ASTM C618
- Ground granulated blast furnace slag (GGBFS) Grade 100 complying with ASTM C989
- Type S masonry mortar complying with ASTM C270
- Hollow concrete masonry units (CMUs) complying with ASTM C90
- Coarse aggregate - 9.5 mm (3/8-in.) pea gravel complying with ASTM C404
- Fine aggregate - Washed concrete sand complying with ASTM C404
- Steel reinforcement complying with ASTM A615
- Potable Water

Trial grout proportions, by volume, followed the upper bound on aggregates from Table 1 of ASTM C476. No chemical admixtures were added to any of the grout mix designs. Cementitous material consisted of three types,

- 100% Portland cement – traditional mix design,
- 50% to 70% Portland cement replaced by Type F fly ash, and
- 60% to 80% Portland cement replaced by a combination of Type F fly ash and GGBFS.

The 100% Portland cement (traditional mix design) was the base-line mix design and represents the most commonly used grout in industry. This traditional mix design requires vibration for consolidation and reconsolidation. The proportions for cementitious material and the complete mix designs are shown in table below [Table 1].

The material proportions were batched by volume and mixed in a mechanical mixer per ASTM C476.

Table 1. Percentage of Fly Ash and GGBFS Replacement of Portland cement in Grout Mix Design

Mix Design Percentage by Volume of Individual Material Portion						
Test Name	**Cementitious** (1 Part)			**Fine Agg.** (3 Parts)	**Course Agg.** (2 Parts)	**Water** (1.375 Parts)
	Cement (% Vol.)	Fly Ash (% Vol.)	GGBFS (% Vol.)	Washed Sand	3/8” (9.5mm) Pea Gravel	Potable
50F	50	50	0	100	100	100
60F	40	60	0	100	100	100
70F	30	70	0	100	100	100
60SF	40	15	45	100	100	100
70SF	30	17.5	52.5	100	100	100
80SF	20	20	60	100	100	100
100C	100	0	0	100	100	100

##F indicates the percent replacement of Portland cement with Fly Ash

##SF indicates the percent replacement of Portland cement with a combination of Fly Ash and GGBFS. In all cases the Fly Ash was kept at a constant of 25% of the replacement combination

100C indicates the use of 100% Portland cement

3 CONSOLIDATION RESULTS

The Masonry Society (TMS) Specification for Masonry Structures (TMS 602) recommends thorough quality control procedures to help assure good consolidation. Quality control procedures include specifications for quality materials, consistent mixing techniques, and certified placement by professionals.

In industry, quality control procedures are typically part of a project and are very important for a level of assurance of structural behavior of the final construction. For the discussion of this paper the grout quality control procedures of the investigation can be considered to be

- use of quality materials through conformance to ASTM standards for materials;
- consistent mix design by having consistency in measuring, mixing, and delivering; and
- consistency in construction techniques including placement and curing.

3.1 Quality Control

When quality control procedures are followed the self consolidating grout should meet the criteria outlined in ASTM C1611 (Slump Flow for Self Consolidating Concrete). The acceptable criteria are a slump flow between 21 in. (533 mm) and 29 in. (736 mm) and a visual stability index (VSI) of 1. The results for ASTM C1611 criteria slump flow and VSI were as follows [Table 2].

Table 2. Slump Flow and Visual Stability Index

Reported Slump Flow Test Results						
Grout Mixture	Grout Mix 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.)b	VSI	T_{50}, (seconds)
50F	1-1-1	25.00	25.50	25.25	1	1.0
50F	1-1-2	25.75	26.50	26.12	1	0.8
60F	1-2-1	28.00	28.00	28.00	1	1.4
60F	1-2-2	29.25	27.75	28.50	1	0.8
70F	1-3-1	29.50	29.00	29.25	1	1.0
70F	1-3-2	28.75	28.25	28.50	1	1.0
60SF	2-1-1	24.00	24.00	24.00	1	1.6
60SF	2-1-2	26.00	24.00	25.00	1	1.0
70SF	2-2-1	26.50	26.00	26.25	1	0.8
70SF	2-2-2	26.50	25.00	25,75	1	1.0
80SF	2-3-1	27.25	26.00	26.62	1	1.2
80SF	2-3-2	27.50	26.00	26.75	1	1.2

3.2 Reinforcement Encapsulation

The American Concrete Institute (ACI) subcommittee 506.2 (Specifications for Shotcrete) made recommendations for quantifying encapsulation of reinforcing bars. The quantifying recommendations are given in a preliminary Technical Note, where comparison of any crack or void lengths and void areas are made to the rebar circumference and area. The comparisons are percentage based. For example, rebar encapsulation is considered excellent if 90% or more of the circumference of the rebar is enclosed by the shotcrete. The rebar is considered to have good encapsulation if 85%-90% of the rebar is enclosed by shotcrete.

The investigation of this report used #5 rebar (0.625 in. (16 mm) diameter), which has a circumference of 1.96 in. (50 mm) and an area of 0.31 in^2 (200 mm^2). Using the criteria of the preliminary Tech. Note, the passing values (rated fair or higher) for a #5 rebar would be as follows.

a. Encapsulation Circumference: Greater than 75% of Circumference = 1.47 in. (37 mm) or 0.49 in. (13 mm) void length touching rebar.
b. Maximum Void Size Touching Rebar: Less than 35% of rebar area = 0.109 in^2 (70 mm^2) or a void length of 0.50 in. (13 mm) x 0.217 in. thick (6 mm).

The quantifying recommendations given in the preliminary Tech. Note are shown in [Table 3] [6].

Table 3. ACI Tech. Note Subcommittee 306.2 on Reinforcement Encapsulation for Shotcrete

FUTURE TECH NOTE - PRELIMINARY

TECHNICAL NOTE – EVALUATION OF CORES

Evaluation is based on degree of encapsulation of steel and the size and location of voids.

- Cores are graded in broad categories for each criteria.
- The contract documents should specify a minimum grade category for acceptance.
- For a specific core grade, all 3 criteria (a, b, and c) should be satisfied.
- Based on project conditions, the specifier may chose additional latitude.

	CRITERIA	Excellent Very good	Good to very good	Fair	Poor
a	Encapsulation of reinforcing steel as a % of the circumference of the bar (any individual bar cross-section or total of all bars in the core);*	90	85 to 90	75 to 80	<75
b	Maximum size ** of any void touching the reinforcing bar, as a percentage of the cross-section of that bar; and	25%	30%	35%	>35%
c	Maximum total area*** of other voids, as a percentage of the total cylindrical surface area of the core***.	10%	15%	20%	>20%

In this investigation, consolidation specimens were cut from a 12.67 ft. (3.86 m) high wall where the grout was placed in one lift. The specimens were cut at portions of the wall that contained two #5 (each 0.625 in. (16 mm) diameter)horizontal rebar. The vertical spacing of the rebar was 24 in. (610 mm) o.c. beginning at 20 in. (508 mm) from the bottom of the wall. In the specimen identification the height of the rebar location as measured from the bottom wall was ordered from A to F. The rebar located closest to the bottom was labeled “A” (20 in. height) and the rebar specimen farthest from the bottom was labeled “F” (140” height).

Selected specimen measurements of encapsulation are given in [Table 4] below. The measurements with a single value (e.g. 0.75” void) indicates a circular void. Also, given is the rating of encapsulation as recommend in the ACI Tech. Note [Table 5].

Table 4. Grout Mix Design Rebar Encapsulation Measurements

	Grout Mix Design Measurement of Voids Touching Rebar (void thickness x length)							
Specimen Height ID	100C-NC	100C-C	80SF	70SF	60SF	70F	60F	50F
A	1/16"x1/8"	none	3/4" void	none	-	1/4"x7/8"	-	1/8"x3/4"
B	none	1/16"x1"	1/8"x3/4"	-	3/4" void	-	1/8"x3/8"	-
C	1/16"x3/4"	none	void between	-	1/16"x1/2"	1/16"x5/16"	1/8"x1/2"	none
D	1/16"x3/4"	1/8"x1/4"	1/8"x1/4"	1/16"x1/8"	1/4"x5/8"	1/16"x1/8"	1/8"x1/2"	1/8"x5/8"
E	1/16"x3/8"	1/8"x1/4"	1/8"x3/8"	1/8"x5/8"		none	-	1/16"x1/2"
F	1/16"x3/4"	-	1/16x1/8"	-	1/4"x1/2"	1/8"x1/4"	-	1/8"x1/2"

Table 5. Grout Mix Design Rebar Encapsulation Ratings

	Grout Mix Design Rating of Rebar Encapsulation per ACI Preliminary Tech Note							
Specimen Height ID	100C-NC	100C-C	80SF	70SF	60SF	70F	60F	50F
A	Excellent	Excellent	POOR	Excellent	-	POOR	-	POOR
B	Excellent	POOR	POOR	-	POOR	-	FAIR	-
C	POOR	Excellent	POOR	-	FAIR	GOOD	FAIR	Excellent
D	POOR	Excellent	Excellent	Excellent	POOR	Excellent	FAIR	POOR
E	FAIR	Excellent	FAIR	POOR		Excellent	-	FAIR
F	POOR	-	Excellent	-	FAIR	Excellent	-	FAIR

The measurements of voids in the traditional non-consolidated grout and consolidated grout agree with expectations of consistent voids throughout the grout column height for the non-consolidated grout and minimal to no voids throughout the grout column height for the consolidated grout. It is noted that perfection is rarely obtained and consolidated grout column does have one specimen with a non-conforming void, but the general results of consolidation is minimal to no voids.

The measurements of voids in the self-consolidating grout confirm expectations of having minimal voids near the bottom of the wall where the pressure head of the self weight of the grout column helps in consolidation. The voids in the self-consolidating grout had a tendency to increase in thickness near the top of the wall. This increase in thickness of void agrees with a small pressure head at the top of the walls.

The ACI preliminary Tech. Note ratings give an indication that encapsulation of the self-consolidating grout has the potential to provide excellent encapsulation for the lower half of the wall.

4.0 Conclusion

The first investigations of sustainable self-consolidating grout show great potential for application. The relative void thicknesses of the self-consolidating grout under horizontal rebar compare very well with the baseline of traditional grout with mechanical vibration. Both grout mix designs (traditional and self-consolidating) consistently maintained void thickness of 0.125 in. (3 mm) or less. The stability of the self-consolidating grout was excellent throughout out the grout columns and for all mix designs – no segregation was found. The ASTM 1611 visual stability index was consistently rated as ONE, for all mix designs.

When the ACI preliminary Technical Notes for rating reinforcement encapsulation of shotcrete are used as a gauge for encapsulation of reinforcement in grout – traditional grout with mechanical vibration consistently rated excellent throughout the height of the wall, with one exception. All mix designs of the self-consolidating grout had acceptable ratings for the lower half of the wall – where self weight pressure head is the greatest. It is noted that the fly ash only self-consolidating mix design with the highest percentage of fly ash rated excellent for encapsulation of reinforcement on the lower half of the wall as did the fly ash and GGBFS mix design, the mix design with the highest amount of fly ash rated excellent. This is most likely due to the lubricating characteristic of fly ash (as evidenced by measured flow).

Further research is needed in order to address the consolidation issues encountered in the upper 6 ft. (1.8 m) of the wall (lower pressure head).

ACKNOWLEDGEMENTS

The following organizations have supported the study and without their monetary, material and labor contributions, the test program would not have been possible:

- Concrete Masonry Association of California and Nevada,
- Masonry Institute of America,
- Pacific Coast Building Products,
- Basalite Concrete Products,
- Bricklayers & Allied Craftworkers Local Union No. 4, and
- Coastal Demo Inc.

REFERENCES

1. Huntzinger, D., Gierke, J., Kawatra, K., Eisele, T. and Sutter, L,; “Carbon Dioxide Sequestration in Cement Kiln Dust through Mineral Carbonation”; *Environmental Science & Technology*; Vol. 43: 6, (2009)
2. E. Sakai, S. Hoshimo, Y. Ohba, and M. Daimon; “The Fluidity of Cement Paste with Various Types of Inorganic Powders” *Proceedings of the10th International Congress on the Chemistry of Cement*; Sweden (1997).
3. Bonen, D. and Shah, S.; “Fresh and Hardened Properties of Self-Consolidating Concrete”; Progress in Structural Engineering and Materials; Vol. 7.1: 14-26. (2005)
4. Khayat, K.H.; “Workability, Testing, and Performance of Self-Consolidating Concrete”; ACI Materials Journal; 96-M43. (1999)
5. Greenwald, J., Breeding, D.L., Luttrell, M.D., Ross, D.H., Carter, C.C. and Rouhani. E. ; “Self-Consolidating Grout Investigation: Compressive Strength, Shear Bond, Consolidation and Flow”; National Concrete Masonry Association; 04-355. (2006)
6. Ragland, J.; “Evaluating/Assessing Encapsulation of Reinforcing in Shotcrete”; *ACI Spring Convention 2012*; Dallas, TX, March 18-22, 2012.
7. American Society for Testing and Materials. ASTM Standards, ASTM International:
    - A615, Standard Specification for Deformation and Plan Carbon-Steel Bars for Concrete Reinforcement, 2009.
    - C90, Standard Specification for Loadbearing Concrete Masonry Units, 2009.
    - C150, Standard Specification for Portland Cement, 2009.
    - C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, 2008.
    - C270, Standard Specification for Mortar for Unit Masonry, 2008.
    - C404, Standard Specification for Aggregates for Masonry Grout, 2007.
    - C476, Standard Specifications for Grout Masonry, 2010.
    - C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, 2008.
    - C989, Standard Specification for Slag Cement for Use in Concrete and Mortars, 2009.
    - C1019, Standard Test Method for Sampling and Testing Grout, 2011.
    - C1611, Standard Test Method of Slump Flow of Self-Consolidating Grout, 2009.