# SELF-CONSOLIDATING GROUT INVESTIGATION: MAKING AND TESTING PROTOTYPE MIX DESIGNS

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## SUMMARY

Prototype Coarse and Fine self-consolidating grout (SCG) trial mixtures for use with masonry construction were developed under laboratory conditions. These mixes were developed to provide guidance for SCG mix designs and to evaluate current and develop new testing procedures for quality control of SCG.

## INTRODUCTION

Grouting to provide bond between reinforcement and masonry is a labor-intensive and time consuming portion of reinforced masonry construction. By referencing the *Specification for Masonry Structures*, ACI 530.1/ASCE 6/TMS 602 [MSJC, 2005], the *International Building Code* [ICC, 2003] requires that each grout lift be consolidated before the next lift is placed to eliminate voids and help ensure complete grout fill and good bond. Each lift must also be subsequently reconsolidated. In addition, mortar protrusions, or fins, extending more than 13 mm (½ in.) into cells to be grouted are required to be removed to prevent them from interfering with grout flow and proper consolidation. The *Specification for Masonry Structures* also requires the grout the meet the requirements of ASTM C 476, *Standard Specification for Grout for Masonry* [ASTM, 2002] which include material requirements for Coarse grout that contains a combination of 9.5mm (3/8 in.) stone and sand, as well as for Fine grout that contains only sand.

As an alternative to the standard placement procedures, the *Specification for Masonry Structures* provides for variation in the grouting procedures if a grout demonstration panel is constructed prior to masonry construction to show that a high quality end product is obtained. This provision has been successfully utilized on numerous projects using self-consolidating grout (SCG) to eliminate the need for consolidation and reconsolidation.

SCG is a highly fluid and stable grout mix that is easy to place. It is a flowable yet highly cohesive material that will not segregate and can pass freely through congested reinforcement and narrow openings without 'blocking or bridging'. It does not require vibration and will self-level and self-consolidate within the CMU cores. SCG must maintain its fluidity without segregation to produce a mix that results in consistent properties throughout the grout lift. It is composed of cementitious materials, aggregates, water, and admixtures which provide the fluidity and stability to meet performance requirements.

This research was conducted to develop some expertise in SCG mix designs. Prototype Coarse and Fine SCG mixes were developed to help give mix design guidance to potential producers and users of SCG. This research addressed: performance requirements of SCG mixes, optimum component levels for successful SCG mixes, development of lab tests and criteria for evaluating SCG mixes, identification of appropriate tests for field testing of SCG mixes, and relative grout compressive strengths (ASTM C 1019, *Standard Test Method for Sampling and Testing Grout* [ASTM, 2005]) of selected mixes. Design methodology and testing requirements were built on existing knowledge of Self-Consolidating Concrete (SCC). Essentially, SCG is a special application for SCC – grouting of masonry wall construction.

## MIX DESIGN METHODOLOGY AND RAW MATERIALS

At the most basic level, SCG needs a 'sea' of paste and fine aggregate in which the coarse aggregate can be suspended. Since the paste is the vehicle for the transport of the aggregate, the volume of paste must be greater than the void volume in the aggregate. There must be enough paste and fine aggregate to surround and fully coat each coarse aggregate particle so that it does not interlock with adjacent particles. The amount and size of coarse aggregate must be limited so that it can remain suspended in the 'sea' of paste without blocking or bridging as it passes through congested reinforcement and narrow openings. The paste and fine aggregate fraction must also have enough viscosity and cohesiveness to keep the coarse aggregate particles suspended to ensure that they do not settle and segregate from the remainder of the mix during the placement and hardening of the SCC/SCG.

Adequate paste content is critical for making stable SCG mixes because the paste forms the matrix in which the particles are suspended. This paste is composed of powder, water and entrained air, if any. Likewise, the powder is composed of all cementitious materials and those materials finer than the 0.150 mm (No. 100) sieve. The powder in many mixes contains auxiliary materials including pozzolanic and hydraulic materials as well as inert fillers such as ground limestone. These additions to the cement can improve and maintain cohesion and segregation resistance of the mix while lowering the overall cost and helping to control the ultimate strength of the mix. In this study, the SCG mixes were made with combinations of Type I/II portland cement (Cem) and Class F fly ash (FA), typically at a 2:1 ratio by weight.

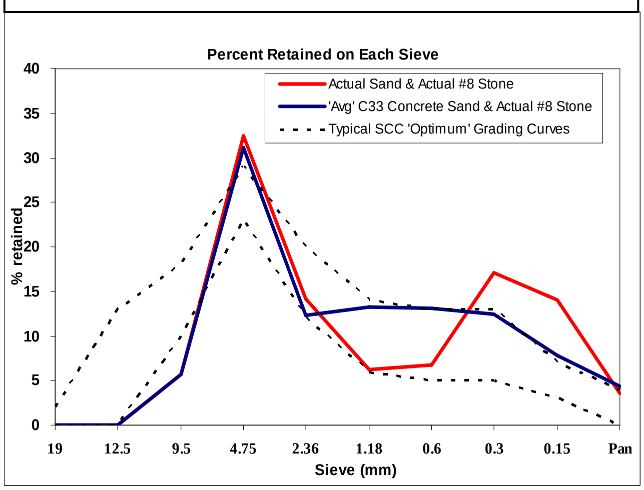
The aggregate blend used in SCG is important, since stable mixes are easier to achieve when the aggregates fit well together. In addition, the passing ability is influenced by the maximum aggregate size. Most SCC guidelines recommend a maximum particle size of 12.5 mm (0.5 in.) or less, since large particles are the hardest to suspend in the paste. The actual maximum aggregate size for any given applications is limited mainly by the spacing of reinforcement in that application.

ASTM C 476 requires that the aggregates in masonry grout meet the requirements of ASTM C404, *Standard Specification for Aggregates for Masonry Grout* [ASTM, 2004]. ASTM C404 limits the maximum coarse aggregate size in grout to 9.5 mm (3/8 in.). Since this gradation has been used successfully with the reinforcement encountered in masonry grout applications, this gradation was assumed acceptable for use in SCG and used for this project.

The aggregates used in this study were supplied by a local ready-mix producer and were the regular aggregates that the producer uses to make grouts in accordance with ASTM C 476. The coarse aggregate was a fairly angular, dense stone with an FM of 5.63. Its gradation met the requirements of a Size No. 8 Coarse Aggregate in accordance with ASTM C 404.

The fine aggregate was a manufactured concrete sand with an FM of 2.49. Its gradation essentially met the requirements of a Size No. 1 Fine Aggregate in accordance with ASTM C 404, and by extension the requirements for concrete sand in accordance with ASTM C 33, *Standard Specification for Concrete Aggregates* [ASTM, 2003], although the amount of material passing the 0.600 mm (No. 30) and 0.300 mm (No. 50) sieves was just above the allowed maximum. It was decided to proceed with this aggregate since it represents a typical "real-world" aggregate used by a ready-mix supplier.

**Figure 1: Comparison of Actual Sand vs. 'Average" Concrete Sand**




The aggregates were blended in the first mixes to achieve a targeted 0.58 sand to total aggregate (s/a) ratio and the s/a ratio for all of the mixes ranged from 0.52 and 0.58. The blending was performed to achieve a grading curve similar to 'optimum' grading curves for SCC. Figure 1 shows how the actual blend compared to a typical SCC optimum grading curve. The figure also shows the expected grading curve for this #8 stone combined with an 'average' concrete sand.

Several types of admixtures were used in this project. The primary polycarboxylate based high-range water-reducing admixture (referred to as PC1) is a fairly basic PC that is recommend primarily for ready-mix concrete applications and is formulated to comply with the requirements of a Type F Admixture (Water Reducing, High Range) in accordance with ASTM C 494/C 494M, *Standard Specification for Chemical Admixtures for Concrete* [ASTM 2005]. It has successfully been used in SCC, often with a viscosity-modifying admixture added. Its

recommended dosage rate is 195 to 590 mL/100kg (3 to 9 oz/cwt) of cementitious material. The actual dosages used in this study varied greatly, but the design methodology followed was to adjust the PC to achieve the targeted slump flow.

The viscosity-modifying admixture (referred to as VMA1) used in this project was developed to be used in SCC mixes and is designed to increase the viscosity of the mix while still allowing it to flow without segregation. Its recommended dosage rate is 390 to 1550 mL/m$^3$ (10 to 40 oz/yd$^3$) of concrete. The actual dosages used in this study varied greatly, but the design methodology followed was to adjust the VMA to achieve the targeted $T_{50}(T_{20})$ time.

Some of the batches include a water-reducing admixture (referred to as WR1) which is formulated to comply with the requirements of ASTM C 494/C 494M Type A (Water Reducing) Admixture at lower dosage rates and Type D (Water Reducing and Retarding) at higher dosage rates. Its recommended dosage rate is 130 to 520 mL/100 kg (2 to 8 oz/cwt) of cementitious materials. It was used with the base mix to achieve the targeted 'natural' slump before the PC1 was added to transform the base mix into SCG.

## TEST PROCEDURES

Slump flow, $T_{50}(T_{20})$ and VSI were determined in accordance with ASTM C 1611/C 1611M, *Standard Test Method for Slump Flow of Self-Consolidating Concrete* [ASTM 2005]. Two tests for static stability commonly used with SCC were also performed on some batches. The first was the Column Segregation Test. The procedure used was that outlined by Daczko [Daczko, 2004]. This procedure has since been developed into ASTM C 1610/C 1610M, *Standard Test Method for Static Segregation of Self-Consolidating Concrete Using the Column Technique* [2006], which was published after the testing performed in this project. The other static stability method evaluated was the Sieve Segregation Resistance Test described in Annex B.4 of *The European Guideline for Self-Compacting Concrete – Specification Production and Use* [Self-Compacting Concrete European Project Group, 2005].

**Table 1: Rating Scale for Self-Healing Test**

| | |
|---|---|
| Excellent | 'S' flows back together completely with no visible evidence of the 'S' remaining |
| Very Good | 'S' flows back almost completely with only slight evidence of the 'S' visible as a sheen |
| Good | 'S' flows mostly back together with an indentation of up to 1/8 in. (3mm) at the surface and some bleed water visible in the 'S' |
| Fair | 'S' only partially flows back together with an indentation of up to half of the patty thickness and significant bleed water and minor aggregate segregation in the 'S' |
| Poor | 'S' does not flow back together with an indentation of more than half the patty thickness and severe aggregate, paste and water segregation in the 'S' |

Another test used to determine stability was the "Self-Healing" test. This test is done after the slump flow, $T_{50}(T_{20})$ and VSI have been recorded. An 'S' (about 250 to 300 mm (10 to 12 in.) in height) is drawn in the SCG patty with a finger making sure to scrape off the SCG all the way down to the board. The patty is observed to see if the 'S' will self-heal. In cases where the self-healing is excellent, the SCG flows back together and there is little or no evidence of the 'S' remaining. In cases where the self-healing is poor, the SCG does not flow back together and the 'S' remains very visible with severe aggregate, paste and water segregation. Due

to observations during this project, a Self-Healing (after agitate) test was created. After completion of the standard Self-Healing test, the SCG patty is vibrated and a second test is done and designated Self-Healing(after agitate). To vibrate the mix, the side of the slump flow base-plate platform was lightly tapped or kicked six times with a foot (three on one side followed by three on a side that was orthogonal [right-angle] from the original side). After disturbing the sample, the "S" test was repeated and a second rating is determined. The laboratory conditions that led to the creation of the Self-Healing (after agitate) procedures are documented below. For both the standard Self-Healing and the Self-Healing(after agitate) tests, the subjective rating scale in Table 1 was used. This rating scale was developed during this project and can be used in practical SCG applications to qualitatively measure the self-healing ability of SCG mixes.

## TESTING RESULTS AND DISCUSSION

SCG mix design targets were developed based on *The European Guideline for Self-Compacting Concrete – Specification Production and Use* (referred to herein as the European Guidelines) combined with practices and guidelines used in the USA that have historically proven successful to produce SCC and ASTM C 476 masonry grouts. The mix design targets are shown in Table 2.

In all, 71 separate batches of grout were developed, mixed, and tested. Each batch was given an identification number in the format XXX-YY where XXX represents the day of the year that the batch was made and YY is the sequential batch number. For example, Batch ID 263-69 was made on the 263$^{rd}$ day of the year (Sept 30) and was the 69$^{th}$ batch made during the project.

Table 2 summarizes the most successful batches during the course of mix design trials. Batch 178-0 is the initial Coarse grout control batch. This batch was based on the ASTM C 476 guidelines for Coarse grout and represents the mix usually supplied by a local ready-mix grout supplier. The natural slump of this batch was 185 mm (7.25 in.) without the use of WR1 which is slightly below the 205 mm (8 in.) minimum for ASTM C 476 grout. This slump was targeted because the local ready-mix grout supplier typically uses a water-reducing admixture (which was not available during this phase of the project) that would increase the slump to about 230 to 270 mm (9 to 10.5 in.) for the same water content. This slightly stiffer mix should yield compressive strengths that are representative of the supplier's normal grout containing the admixture. Batch 308-71 is the control Fine grout mix, based on the ASTM C 476 guidelines for Fine grout.

The following is a discussion of the testing results in regards to the specific variables evaluated.

### Aggregates

The aggregates used in this project for SCG are exactly those that are already specified in ASTM C 476 for conventional masonry grouts. It was found that these aggregates are suitable for creating stable SCG mixes. The coarse aggregates have a limited top size of 9.5 mm (3/8 in.) and have proven passing and filling ability in reinforced masonry application. The limited top size makes them ideal for making a self-consolidating mix. The concrete sand used in the Fine SCG mixes also proved suitable for use in SCG.

**Table 2: Summary of most successful batches**

| | | Coarse Grouts | | | | Fine Grouts | |
|---|---|---|---|---|---|---|---|
| **Batch ID** | **Targets** | **178-0** | **181-16** | **182-28** | **263-56b** | **308-71** | **308-70** |
| **Title** | **Initial Mix Design Targets** | **Control C476 Coarse Grout** | **700 Std SCG 1b** | **750 52%s Std SCG1** | **PC1 Trial 1: Optimum** | **Control C476 Fine Grout** | **PC1 Trial 4: Optimum** |
| ***As Designed(kg/m $^3$ )*** | | | | | | | |
| Cement | 297 | 358 | 277 | 297 | 297 | 446 | 316 |
| Fly Ash | 148 | 0 | 138 | 148 | 148 | 0 | 158 |
| Total | 445 | 358 | 415 | 445 | 445 | 446 | 474 |
| ***Composition*** | | | | | | | |
| % Sand (abs vol of total agg) | 50 - 60 % | 64% | 58% | 52% | 53% | 100% | 100% |
| Total Cementitious (kg/m $^3$) | 445 | 363 | 419 | 449 | 447 | 450 | 454 |
| Total Powder (kg/m $^3$) | --- | 430 | 483 | 511 | 507 | 513 | 516 |
| w/cm | 0.40 - 0.45 | 0.630 | 0.507 | 0.456 | 0.490 | 0.620 | 0.580 |
| Water (kg/m $^3$) | --- | 229 | 212 | 205 | 219 | 279 | 263 |
| Vol Water/Powder | 1.01 - 1.13 | 1.63 | 1.26 | 1.15 | 1.24 | 1.67 | 1.46 |
| ***Admixtures*** | | | | | | | |
| PC1 (mL/100 kg) | as needed | - | 590 | 555 | 460 | - | 460 |
| VMA1 (mL/m $^3$) | as needed | - | 1060 | 1080 | 1160 | - | 930 |
| ***Plastic Properties*** | | | | | | | |
| Plastic Density (kg/m $^3$) | --- | 2380 | 2395 | 2420 | 2365 | 2110 | 2085 |
| Paste Volume | 34 - 40% | 37% | 38% | 38% | 41% | 50% | 50% |
| Mortar Volume | 68 - 72% | 71% | 69% | 66% | 68% | 92% | 92% |
| Calc Air Content* | | 0.8% | -0.9% | -1.0% | 1.1% | 5.1% | 5.8% |
| Slump Flow or Slump (mm)** | 660 - 710 | 185 | 700 | 685 | 660 | 270 | 685 |
| $T_{50}$ (sec) | 2.0 - 3.5 | nd*** | 2.4 | 3.3 | 2.3 | nd | 1.5 |
| VSI (#) | 0 - 1 | nd | 0 | 1 | 0 | nd | 0 |
| VSI (Description) | --- | nd | nd | Slight halo, sheen &agg pile | No halo, no sheen. | nd | No sheen or halo. |
| Self Healing Test | Good-Excellent | nd | Good | Very Good | Excellent | nd | Excellent. |
| Self Healing (after agitate) | Good-Excellent | nd | nd | Good | Very Good | nd | Very good. |
| ***C1019 Grout Prisms (MPa)*** | | | | | | | |
| 28 days (Avg of 3 prisms) | 34.5 - 55 | 38.3 | 39.0 | 42.4 | 37.4 | 30.7 | 23.5 |
| 91 days ( Avg of 3 prisms) | | 40.6 | 53.1 | 56.9 | 49.8 | 34.9 | 37.6 |
| ***Relative C1019 Grout Prisms*** | | | | | | | |
| 28 days (Avg of 3 prisms) | 75% - 125% | 100% | 102% | 111% | 98% | 100% | 77% |
| 91 days ( Avg of 3 prisms) | | 100% | 131% | 140% | 123% | 100% | 108% |

* Calc Air Content calculated from weight of 0.0028 m3 (0.10 ft3) container. Values < 0 are due to normal testing variance.
** Values >305 mm = Slump Flow. Values < 305 mm = Slump.
*** nd = not determined

## Cementitious Materials

As a reference and for comparison purposes, a typical conventional Coarse grout made to the proportion specifications of C 476 will contain about 325 to 415 kg/m $^3$ (550 to 700 lb/yd $^3$) of cementitious materials. We found that we could make stable SCG mixes with 445 kg/m $^3$ (750 lb/yd $^3$) of total cementitious content containing 33% Type F Fly Ash and 67% Type I/II portland cement, such as batch 263-56b (See Table 2). This batch was the most successful Coarse SCG batch of the project. This mix had compressive strength values that were within our design targets of 34.5 MPa (5000 psi) target, 55.2 MPa (8000 psi) maximum at 28 and 91 days, and 75 to 125% of the control conventional grout strength at 28 days.

A limited number of stable SCG mixes were made with 415 kg/m $^3$ (700 lb/yd $^3$) total cementitious content, such as batch 181-16. We were not successful in making stable SCG with only 385 kg/m $^3$ (650 lb/yd $^3$) total cementitious content as these batches all had poor stability with VSI ratings of 2 to 2.5 with halos and slight aggregate piles being visible after the slump flow testing.

## Mix Design Methodology

The first batches were made targeting an initial ‘natural’ slump of 25 to 100 mm (1 to 4 in.) with the subsequent addition of PC1 and VMA1 to achieve the desired slump flow and $T_{50}$($T_{20}$) time. These batches, such as 182-28, seemed good, but showed instability when subjected to vibration.

Attempts were next made to follow recommendations in the European Guidelines by limiting the amount of water to get natural slumps of 0 to 25 mm (0 to 1 inch). These batches required higher dosages of PC1 to achieve the desired slump flow. These batches had only fair self-healing. It was speculated that the PC1 had possibly been overdosed to get the required slump flow.

The most successful Coarse SCG batches (such as 263-56b) made utilized the following methodology: limit the PC to a reasonable dosage (75-85% of recommended maximum) and adjust the water content to achieve a slump flow of 660–710 mm (26–28 in.). This equated to having a natural slump of approximately 180–230 mm (7-9 in.) prior to adding PC1 or VMA1.

For the Fine SCG, the same successful methodology was used. This equated to having a natural slump of approximately 255 mm (10 in.) prior to addition of PC1 or VMA1. This methodology was used to create the most successful Fine SCG batch, 308-70.

Table 1 also shows the results of the C 1019 compressive strength testing of grout prisms. SCG normally has a higher compressive strength than conventional grout; mainly due to higher cementitious materials content in SCG. However, it is also important that the SCG strength be fairly comparable to a conventional grout, since it is desirable for a grout to have a compressive strength somewhat similar to that of the corresponding concrete masonry unit so that the physical properties of the grout and CMU will be similar. For the Coarse SCG batches, 263-54b had the best compressive strength results compared to the target values. For the Fine SCG batches, 308-70 had compressive strengths that were also within the targeted limits.

## Suitability of Segregation Tests

Several mixes were used to determine the suitability of SCC segregation tests on the SCG mixes. Testing was performed to evaluate both the Colum Technique for Static Segregation (ASTM C 1610) and the European Sieve Segregation Test. The results for the Column Segregation test are shown in Table 3. These results show that this test was unable to tell stable and unstable mixes, as determined by VSI, from one another.

**Table 3: Results of Column Segregation Testing**

| **Batch ID** | **179-2** | **179-5** | **179-7** | **180-9b** | **181-18 (st)** |
|---|---|---|---|---|---|
| **Title** | **750 Trial 1** | **750 Std SCG 1** | **700 Std SCG 1** | **650 Trial 2 +1.0 PC1** | **Low FA Trial 2 End** |
| ***Properties at 0% air*** | | | | | |
| Plastic Density (kg/m$^3$) | 2365 | 2390 | 2415 | 2410 | 2430 |
| Paste Volume | 41% | 39% | 37% | 36% | 36% |
| Mortar Volume | 71% | 70% | 69% | 68% | 68% |
| Slump Flow | 760 | 725 | 660 | 660 | 660 |
| $T_{50}$ (sec) | 0.7 | 2.7 | 3.5 | 2.6 | 2.9 |
| VSI (#) | 1 | 0 | 0 | 2.5 | 2 |
| VSI (Description) | nd | nd | nd | Halo & Slight Agg. Pile | Halo, sheen, bleeding & very slight agg. pile |
| ***Colum Static Segregation*** | | | | | |
| % + 2.36 mm Sieve in Top Section | 43.7% | 39.3% | 42.4% | 44.4% | 41.1% |
| % + 2.36 mm Sieve in Bottom Section | 41.5% | 40.9% | 42.5% | 44.2% | 42.2% |
| **CSF %** (Column Segregation Factor) | **0.0** | **3.9** | **0.2** | **0.0** | **2.6** |

nd = not determined

The results for the European Sieve Segregation test are shown in Table 4. This test method was also unable to distinguish between stable and unstable mixes. It is not clear if these results were a function of our particular raw materials or a general characteristic of Coarse SCG mixes

**Table 4: Results of Sieve Segregation Testing**

| Batch ID | 238-35 | 238-36 | 238-37 |
|---|---|---|---|
| Title | Mix 1a | Mix 1b | Mix 1c |
| *Properties at 0% air* | | | |
| Plastic Density (kg/m$^3$) | 2380 | 2405 | 2330 |
| Paste Volume | 38% | 38% | 40% |
| Mortar Volume | 69% | 69% | 70% |
| Slump Flow | 635 | 620 | 710 |
| $T_{50}$ (sec) | 3.4 | 2.2 | 1.5 |
| VSI (#) | 2 | 1 | 2 |
| VSI (Description) | Slight agg pile, no halo, no sheen | Slight sheen, no halo, no agg pile | Sheen and halo |
| Self Healing Test | good | good | excellent |
| Self Healing Test (after agitate) | fair | good | some settling of paste, good self healing |
| *European Sieve Segregation Resistance* | | | |
| SR(undisturbed) | 1% | 5% | 14% |
| SR(disturbed) | 7% | 9% | 23% |

## Development of the "Self-Healing (after agitate)" Test

While attempting to make C 1019 grout prisms from batch 181-20, an unexpected and disturbing phenomenon was encountered. To make the grout prisms, the lab batch was first dumped from the mixer into a standard mortar pan supported on a hand operated pallet truck and transported about 8 m (25 ft) across the lab to the staging area for the grout prism molds. During this movement the mix and mortar pan were jostled somewhat as the pallet truck moved over uneven surfaces in the lab floor. When fabrication of the prisms was started, it was found that the mix had severely segregated with a significant amount of water "floating" on top and a thick paste and aggregate "mud" stuck to the bottom of the mortar pan. Prisms were not made from this material.

The mix and mortar pan were transported back across the lab, placed in the mixer, and mixed for an additional two minutes. It was then re-tested for slump flow and $T_{50}(T_{20})$. Amazingly, it gave nearly identical performance as the original test with the same slump flow and a $T_{50}(T_{20})$ that was only 0.1 sec different. The VSI rating was the same with only a slight sheen visible on the surface. It was judged again to have a very good self-healing ability during the "S" test although there were some minor amounts of fly ash seen floating in the "S", also seen in the original test.

Since the previous efforts to determine a suitable method for determining static and vibration induced instability were unsuccessful, a new test was adapted to characterize vibration-induced instability. After performing the self-healing test, the side of the slump flow base-plate platform was lightly kicked or tapped several times with a foot. The self-healing ability was re-tested using the "S" test and found that the mix now had very poor self-healing ability. This was the birth of the "Self-Healing (after agitate)" test. This test was used to determine the healing ability in subsequent batches. Stable SCG mixes were found to have 'excellent' initial self-healing, and 'very good' to 'excellent' self-healing after agitation.

## Suitability of C 1019 to SCG Mixes

ASTM C 1019 grout prisms were constructed and tested on several batches in this project. For SCG, the current test method was modified slightly to compensate for the differences between SCG and conventional grout. Currently, conventional grout is placed in the mold in two lifts and each lift is rodded to facilitate consolidation. Since SCG is flowable and does not require consolidation or re-consolidation in the field, the prisms for SCG were made in one lift with no rodding. This technique worked well with no leakage of grout from the molds. The hardened

prisms were adequately filled with no obvious void areas or surface defects. The C 1019 test method appears to be applicable to SCG with only this one minor modification.

## CONCLUSIONS

Prototype batches of Coarse and Fine SCG were developed under laboratory conditions. Several design variables were evaluated, as well as the suitability for current SCC quality control and field tests to be used with SCG. Based on the research performed for this project, the following observations and recommendations are offered:

1. Stable Coarse SCG can be achieved with a total cementitious content of 445 kg/m$^3$ (750 lb/yd$^3$) and there was some success at a total cementitious content of 415 kg/m$^3$ (700 lb/yd$^3$). Although slightly lower cementitious contents may be possible they should not be counted on without considerable prior experience with the given raw materials.

2. Stable Fine SCG batches were developed with a total cementitious content of 475 kg/m$^3$ (800lb/yd$^3$). The influence of lower amounts of cementitious materials on Fine SCG was not evaluated during the course of this project.

3. The successful mixes had fly ash:cement ratios of 1:2 by weight. It is likely that other combinations will also work although it is suggested that a producer explore the use of some type of auxiliary material such as fly ash or an inert fine filler like ground limestone. This can help with the stability of the SCG mix. It can also help limit the compressive strength that is obtained from the mix.

4. Aggregates currently being used in conventional ASTM C 476 Coarse and Fine grout mixes are suitable for use with SCG.

5. The most successful methodology for producing stable SCG was to set a polycarboxylate based high range water reducing admixture to a reasonable dosage and to adjust the water content to achieve the specified slump flow values. For Coarse SCG, this equated to a ‘natural’ slump (using only a regular water-reducing admixture or no admixture at all) of 180–230 mm (7-9 in.) and for Fine SCG a natural slump of 255 mm (10 in.). The level of viscosity-modifying admixture can then be adjusted to achieve the desired $T_{50}(T_{20})$ value.

6. SCC quality control tests for slump flow, $T_{50}(T_{20})$, and VSI as detailed in ASTM C 1611/C1611M are directly applicable to SCG and are good tests for documenting the consistency of the plastic properties of the SCG.

7. The Column Technique for Static Segregation (ASTM C 1610/C 1610M) and European Sieve Segregation Resistance tests did not do a good job of separating stable from unstable mixes in this project, although it is not clear if this was a function of the particular raw materials in this sample or a general characteristic of Coarse SCG mixes.

8. A ‘Self-Healing Ability’ test conducted before and after agitation on the slump flow patty after the VSI is determined seemed to do the best job of separating stable from unstable

mixes. A good SCG mix shows 'Excellent' initial self-healing and 'Very Good to Excellent' self-healing after the slump board is disturbed with six light kicks.

9. ASTM C 1019 grout prism test is directly applicable to testing the strength of SCG with one very minor modification – instead of placing the grout in two lifts with rodding of each lift as is done with conventional grout; SCG is placed in one lift without rodding.

SCG requires considerable attention to detail and more control than conventional ready-mix grout. A ready-mix producer who does not have any experience with SCC should approach making SCG with caution. A ready-mix producer who has experience with SCC should be able to take the guidelines in this research and readily adapt his operation to successfully make SCG.

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