# DEVELOPMENT OF HIGH STRENGTH SELF-CONSOLIDATING CONCRETE MIXTURES FOR USE IN PRESTRESSED BRIDGE GIRDERS

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## ABSTRACT

*The paper documents the development of a high strength self consolidating concrete (SCC) mixture for use in prestressed bridge girders. The goal of the research program was developing an SCC mixture with a release strength of 6,000 psi and 28 day strength of 12,000 psi. Along with the strength requirements, the SCC must meet slump flow, J-ring, and* $T_{20}$ *requirements. The water to binder ratio (w:b), binder content, water content, dosage and type of admixtures, and coarse aggregate content were the variables examined. Almost 50 SCC mixtures were batched and tested. The researchers determined that the total water content was one of the controlling factors in producing low w:b SCC mixtures and that high strength SCC mixtures with one days strengths in excess of 6,000 psi and 28 day strength in excess of 14,000 psi can be developed.*

**Keywords**: Self-Consolidating Concrete, High Strength, Prestressed Bridge Girders, Mixture Proportioning

## INTRODUCTION

Self-consolidating concrete (SCC) is specially proportioned concrete that can be adequately placed and properly consolidated without internal or external vibration. SCC is similar to conventional concrete, in that both are composed of the same constituent materials, however the quantities of those materials may differ and SCC may contain additional chemical admixtures. SCC has been in use for several years in the precast industry where precasters routinely produce SCC mixtures with water to binder ratios (w:b) near 0.40 and compressive strengths of approximately 6,000 psi at 28 days, but the use of high strength SCC mixtures is not as common. This paper explores the development of high strength SCC mixtures with low w:b.

## LITERATURE

Self-consolidating concrete (SCC) is highly flowable concrete that can fill formwork containing congested reinforcement and attain satisfactory consolidation without vibration, and remain homogeneous after placement[1]. The most prominent properties of SCC that distinguish it from conventional concrete are its rheological properties. From Fig. 1, $T_1$ and $T_2$ are the yield stress values. $M_1$ and $M_2$ are the plastic viscosity. Concrete can only flow when the shear stress is greater than the yield stress. The self weight of SCC is large enough to create shear stresses greater than the yield stress therefore enabling SCC to flow under its own weight, while conventional concrete will typically only flow under pumping pressure. To attain segregation resistance, however, the plastic viscosity must be high enough to keep all coarse aggregate suspended in the mixture.

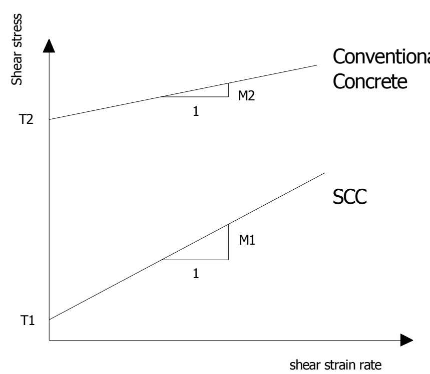


Fig.1 The Bingham Model (Bonen and Shah, 2005)

It is evident that the yield stress is highly dependent on the w:b. As the w:b is increased, the yield stress decreases. However, this leads to a significant reduction of viscosity, which may cause segregation. Furthermore, the strength and durability of the mixture are also reduced. Thus, it is recommended not to increase the w:b when an increase in flowability of the mixture is needed. To solve this problem, the use of superplasticizers or high range water reducers (HRWR) is essential. Using HRWR can significantly reduce the yield stress, which helps the mixture flow. However, adding HRWR has some negative effect on viscosity, but this effect is relatively small compared to the positive effect on the flowability[1].

Bonen and Shah[1] state that the viscosity, coarse aggregate maximum size, and the matrix density are the major factors determining the segregation resistance of SCC. If the viscosity is too high, the mixture will not flow well. Therefore, the other options, aggregate size and matrix density, should be considered. Smaller coarse aggregate will settle more slowly than larger coarse aggregate in the same matrix. Also, smaller coarse aggregate will increase the flow. The matrix density can be improved by increasing the binder content at low w:b. Among the commonly used supplementary cementing materials (SCMs), slag cement is the best choice for segregation resistance due to its high density.

The relationship between the yield stress and viscosity is the key that determines the success of SCC. The yield stress must be low so the mixture is able to flow. The viscosity must be high enough to avoid segregation. In addition, high viscosity assists the movement of coarse aggregate particles along with the paste through obstacles, such as rebar. Otherwise, the paste will pass through the obstacles and leave the coarse aggregate behind resulting in segregation[2].

Typically, the w:b of SCC is low; therefore, SCC is prone to have better hardened properties than those of conventional concrete. The low w:b increases compressive strength and lowers permeability. In addition, SCC typically has improved concrete properties when compared to conventional concrete not containing SCMs. This is the reason that Okamura, who first introduced SCC to the world, named it Self-Consolidating High Performance Concrete[3].

High flowability, segregation resistance, high strength and durability are major properties of SCC. There are three types of SCC: powder type, VMA (viscosity modifying admixture) type, and a combination of both. The powder type has a high volume of binder at low w:b and a high dosage of HRWR. VMA type has the mixture proportions similar to conventional concrete and a HRWR is used to attain the flow and a VMA is used to prevent segregation. The combination type has the mixture proportions somewhat between the binder type and the VMA type along with HRWR and small dosages of VMA [4].

## EXPERIMENTAL PROCEDURE

### SCOPE

Although there are many mixture proportions of SCC in literature, there are very few mixture proportions that provide high compressive strength, especially at 1 day. The goal of the research project was to develop a high strength SCC mixture that can be used in the precast/prestressed industry. For the hardened properties, a one day compressive strength of 6,000 psi was required along with a 28-day strength of 12,000 psi. To ensure that the SCC could flow around and through reinforcement, the SCC mixtures had targeted values of a minimum spread of 26 inches, a maximum J-ring (the height difference between concrete inside and outside the J-ring) of 0.5 inches, a maximum $T_{20}$ of 5 seconds, and a maximum VSI (Visual Stability Index) of 0.5.

## MATERIALS

All materials used in the research program were locally available in Arkansas. For the coarse aggregate, two sizes of crushed limestone with a nominal maximum size of ½ and 3/8 inches were used. Two different sources of Type I cement were also used. Some mixtures also contained silica fume, Class C fly ash, or Gr. 100 slag cement.

To obtain the rheological properties necessary to produce SCC, four different chemical admixtures produced by Grace Construction Products were employed. Table 1 below shows brief descriptions of the admixtures.

Table 1 List of Admixtures.

| | Description | Recommended Dosage | Applications |
|---|---|---|---|
| ADVA 170 | HRWR<br>ASTM Type A and F | 3-9 fl oz /cwt | Low w:b concretes<br>Ready-Mix concrete |
| ADVA 530 | HRWR<br>ASTM Type F | 3-10 fl oz /cwt | Precast and prestressed SCC |
| ADVA 555 | HRWR + VMA<br>ASTM Type F | 8-20 fl oz /cwt | Precast and prestressed SCC |
| V-MAR 3 | VMA | 10-40<br>fl oz / yd of concrete | Precast and prestressed SCC |

## MIXING PROCEDURE

Prior to batching, the coarse and fine aggregate were stored inside the laboratory and the moisture content of the aggregates was measured. The mixtures were then adjusted for the moisture contents of the aggregates. The batch size for most mixtures was approximately 2 $ft^3$.

All SCC mixtures were mixed in a gravity mixer. The mixing sequence followed a modified version of ASTM C 192; the difference being a longer initial mixing time. The longer mixing time allowed for better dispersion of all materials and allowed enough time for the HRWR to work more effectively[5]. As required by ASTM C 192, all coarse aggregate along with half of the mixing water were added to the mixer. The mixer was then turned on and the fine aggregate, binder, and the remaining water were added. Once all the materials were in the mixer, it was allowed to run for 5 minutes followed by a rest period of 2 to 3 minutes, and then a final mixing period of 2 to 3 minutes.

Admixtures were added separately based on the type of admixture. The HRWRs were added to the mixing water. If used, the VMA was added to the concrete during the rest period. When both ADVA 530 and 170 were used, ADVA 170 was added to the mixing water and ADVA 530 was added during the rest period.

## TESTS

The fresh concrete properties tested were slump flow (either regular or inverted) according to ASTM C 1611 (provisional specification), $T_{20}$ (time when the spread of the slump flow test reaches 20 in.), J-ring (provisional ASTM C 1621), unit weight (ASTM C 143), and air content (ASTM C 231). Compressive strength was tested according to ASTM C 39. Cylinders cast for the compressive strength tests were not rodded or tapped. Compressive strength was tested at 1, 7, and 28 days (3, 4 x 8 inch cylinders tested at each age). Cylinders were moist cured at 73 F until time of testing.

DETERMINING SEGREGATION

In addition to the fresh concrete tests previously mentioned, the research team also observed other indicators of possible segregation. The time when concrete is at rest is the most critical time when segregation may occur[4]. Therefore, segregation can be determined when the concrete is resting in the mixer or in a wheel barrel. The indicators are listed below.

- An abundance of bleed water
- 1 inch layer or more of paste on the top surface of the concrete without little or no coarse aggregate
- Coarse aggregate settling to the bottom of the wheel barrel or mixer

## RESULTS AND DISCUSSION

As previously mentioned, the goal of the research project was developing an SCC mixture with a compressive strength of 6000 psi at one day and 12,000 psi at 28 days. In this research, air content was not a concern because the concrete is intended for use in bridge girders and air entrainment often negates the benefits of using high strength concrete in bridge girders. The mixture developed in this study will be used to cast six precast/prestressed concrete beams. The first series of SCC that were developed along with their fresh concrete properties and compressive strength are shown in Table 1.

One of the first steps in the process involved selecting a w:b. For the first mixture, a w:b of 0.31 was chosen based on a review of the literature. These first mixtures incorporated silica fume in an effort to increase compressive strength. Slag cement and fly ash were also used to increase the workability and improve the segregation resistance. To achieve SCC properties, ADVA 555, which is marketed as an admixture for producing SCC, was chosen.

The manufacturer's recommended dosage rate for ADVA 555 is 8 to 20 fl oz./cwt. However for this research program, dosage rates of up to 55 fl oz./cwt were batched in an attempt to attain SCC. Even at this high dosage rate, the viscosity was still too high which prevented the mixture from flowing, and a maximum slump flow of only 22 inches was measured (for mixtures that segregation did not happen). Also, the addition of fly ash and slag cement reduced the one day compressive strength for those mixtures to below 6000 psi. Therefore, future mixtures (Mixtures 11 through 49) did not contain either slag cement or fly ash.

Table 2 SCC Mixtures and Properties (Series 1).

| Materials | Mixtures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 4 | 5 | 7 | 8 | 9 | 10 | 11 |
| Total cementitious materials (lb./ $yd^3$) | 800 | 800 | 900 | 900 | 900 | 900 | 900 | 900 | 900 |
| Slag (%) | 15 | 15 | 15 | 15 | 15 | 15 | 22 | 22 | 0 |
| Silica fume (%) | 6.25 | 6.25 | 6.25 | 6.25 | 6 | 6 | 0 | 0 | 0 |
| Fly ash (%) | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Coarse Agg. (lb./$yd^3$) | 1600 | 1600 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| Fine Agg. (lb./$yd^3$) | 1412 | 1425 | 1426 | 1426 | 1427 | 1427 | 1442 | 1442 | 1455 |
| Water (lb./$yd^3$) | 248 | 248 | 252 | 252 | 252 | 252 | 252 | 252 | 252 |
| Water / Binder | 0.31 | 0.31 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| ADVA 555 (fl oz./ cwt) | 25 | 55 | 45 | 42 | 0 | 12 | 19 | 20 | 0 |
| ADVA 530 (fl oz./ cwt) | 0 | 0 | 0 | 0 | 19 | 10 | 0 | 0 | 18 |
| Fresh Concrete Properties | | | | | | | | | |
| Slump flow (in.) | failed | 22 | 28 | 21 | 29 | 25.5 | 26 | 20 | 23 |
| Segregation observed | no | no | yes | no | yes | yes | no | no | no |
| VSI | - | - | - | - | 2 | 2 | 1 | 0.5 | 1 |
| Air Content (%) | - | - | - | - | - | - | - | 2 | 4.4 |
| Bleed water | no | no | no | - | - | no | no | no | no |
| Compressive Strength (psi) | | | | | | | | | |
| 1-day strength | 4290 | 5550 | 4730 | 5490 | 3380 | 5400 | 5350 | 5430 | 7090 |
| 7-day strength | 11030 | 12240 | 10590 | 11660 | 6460 | 10350 | 11500 | 11120 | 10970 |
| 28-day strength | 13460 | 15500 | 13850 | 14430 | 8070 | 12470 | 14040 | 13480 | 12680 |

Due to low 1-day strength, the w:b for the later batches was reduced to 0.28. In addition, the binder content was increased to 900 lbs/$yd^3$, and the coarse aggregate content was decreased to 1500 lbs/$yd^3$ to get the desired flow. Although the dosage of ADVA 555 decreased (from Mixture 2 to Mixtures 3 and 4), it was still too high and the mixtures generally did not flow well and were viscous. Therefore, another admixture was introduced, ADVA 530. For these 0.28 w:b mixtures (Mixtures 7 through 11), the dosage of ADVA 530 or a combination of ADVA 555 and ADVA 530 was still much higher than the recommended dosage, and the mixtures did not perform well (they did not meet either strength or flow requirements).

In Mixtures 1 through 8, either segregation was observed or the mixtures were too viscous. Silica fume was not used in Mixtures 9 and 10, and the dosage of ADVA 555 went down significantly when compared to Mixtures 1 through 5. However, the mixtures were still too viscous. Also the strength was less than 6000 psi, so to improve 1 day strengths, cement only mixtures were used for the remaining mixtures. Mixture 11, which contained only cement, attained over 7000 psi at 1 day, but the flow was only 23 inches and was still too viscous.

One conclusion made after the first series was that silica fume did not work for the mixtures tested at low w:b. In addition, there was an incompatibility between silica fume and ADVA 555. For the mixtures tested, when ADVA 555 and silica fume were used together, silica fume always rose to the top of the wheelbarrow.

Shown below in Table 3 are the results of the second series of testing (Mixtures 12 to 20). Based on the results of Mixture 11, the cement content was increased, thereby increasing the water content. The dosage of ADVA 530 was reduced to 18 fl oz./cwt and segregation was observed. This showed the importance of the water content in making SCC. From Mixtures 13 to 17, another source of cement was used. Mixture 13 experienced segregation while at rest in the mixer. Then 50 ml of V-MAR 3 was added, and the flow was only 16 inches.

In Series 2, ADVA 170 was introduced at a dosage rate of 4 fl oz/cwt in Mixtures 13, 14, 15, and 18. Additionally, ADVA 530 was used in combination with ADVA 170 in Series 2. Even with the combination of admixtures and the increase in binder content, segregation or high viscosity was observed in Mixtures 12 through 17. To decrease viscosity, the w:b was increased to 0.30 for Mixtures 18 through 20. Mixture 18 contained 4 fl oz of ADVA 170 and 4 fl oz of ADVA 530, but segregation was observed in the mixer. Then 40 ml of V-MAR 3 was added and the flow was reduced to 23.5 in. To improve the segregation resistance, the cement content was reduced to 920 lbs which in turn decreased the water content in the mixtures (Mixtures 19 and 20). However, this decrease in cement content also lowered the compressive strength.

In this series, Mixtures # 13 and 18 experienced segregation and the use of V-MAR 3 reduced the slump flows which demonstrated the effectiveness of the VMA in preventing segregation. In addition, the two mixtures were very workable compared to the previous mixtures.

Since all the mixtures of the first series were either too viscous or segregated, the relationship between the yield stress and the viscosity required improvement. Therefore, the $T_{20}$ test was used in the second series in order to provide information about the viscosity.

Table 3 SCC Mixtures and Properties (Series 2).

| Materials | Mix proportions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 12 | 13[i] | 14 | 15 | 16* | 17* | 18 | 19 | 20 |
| Cement (lb.yd$^3$) | 950 | 950 | 950 | 950 | 950 | 950 | 950 | 920 | 920 |
| Coarse Agg. (lb.yd$^3$) | 1450 | 1450 | 1450 | 1450 | 1450 | 1400 | 1400 | 1400 | 1400 |
| Fine Agg. (lb.yd$^3$) | 1425 | 1425 | 1425 | 1425 | 1425 | 1474 | 1425 | 1474 | 1474 |
| Water Content (lb.yd$^3$) | 266 | 266 | 266 | 266 | 266 | 266 | 285 | 276 | 276 |
| Water /Binder | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.3 | 0.3 | 0.3 |
| ADVA 170 (fl oz. /cwt) | 0 | 4 | 4 | 4 | 0 | 0 | 4 | 0 | 0 |
| ADVA 530 (fl oz. /cwt) | 18 | 10 | 13 | 20 | 0 | 0 | 4 | 10 | 9 |
| Fresh Concrete Properties | | | | | | | | | |
| Slump flow (in.) | 33 | 16 | - | 20 | - | 22.5 | 23.5 | 23.5 | 26.5 |
| T 20 (s) | 5.6 | - | - | - | - | 8 | 5 | 5 | - |
| Time of max spread (s) | - | - | - | 30 | - | 21 | 13 | 15 | 15 |
| Bleed water | yes | - | no | no | - | no | no | yes | no |
| Segregation observed | yes | no | no | no | - | no | - | no | no |
| VSI | 3 | 2 | - | 2.5 | - | 1 | 1 | 0.5 | 0.5 |
| Unit weight | 150.2 | 149.9 | - | - | - | 152.7 | 152.6 | 152.4 | 151.6 |
| Air Content (%) | 0.7 | 2.7 | - | - | - | 2 | 2.1 | 2.1 | 2.2 |
| Compressive strength | | | | | | | | | |
| 1-day strength (psi) | - | - | - | - | - | - | 7430 | 5740 | 5170 |
| 7-day strength (psi) | - | - | - | - | - | - | 12100 | - | 8440 |
| 28-day strength (psi) | - | - | - | - | - | - | 13750 | - | 9770 |

* 18 and 21 fl oz/cwt of ADVA 555 was respectively used for mixture # 16 and 17.

[i] 50 ml of V-MAR 3 was used.

The third series of SCC mixtures is shown below in Table 4. In this series, ADVA 530 and ADVA 170 were used because the research team was not successful in using ADVA 555 at the recommended dosage rates for such low w:b SCC mixtures. In this series, the coarse aggregate was reduced from ½ inch coarse aggregate to a 3/8 inch nominal maximum size aggregate (both aggregates were crushed limestone). These mixtures with the smaller coarse aggregate performed better than those of the second series. All the mixtures were generally workable and less viscous (improved $T_{20}$ times). In addition, the 1-day strengths were close to the desired strength. For Mixtures 22 through 25, the dosages of ADVA 530 were still high and the slump flows were not sufficient. Hence, a combination of ADVA 170 and 530 was used. However, Mixture 26 experienced segregation, and there was bleed water for many mixtures.

Based on the results of this series, both ADVA 170 and ADVA 530 reduced the yield stress of the mixtures significantly; however, ADVA 170 reduced the viscosity more than

ADVA 530. The viscosity of the mixtures was already high; therefore, ADVA 170 was used for later batches in order to attain faster flows (less $T_{20}$).

Table 4 SCC Mixtures and Properties (Series 3).

| Materials | Mix Proportions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| Cement (lb./yd$^3$) | 920 | 950 | 1000 | 950 | 950 | 1000 | 1000 | 950 |
| Coarse Agg. (lb./yd$^3$) | 1450 | 1400 | 1400 | 1400 | 1400 | 1300 | 1300 | 1400 |
| Fine Agg. (lb./yd$^3$) | 1424 | 1475 | 1396 | 1475 | 1450 | 1495 | 1495 | 1425 |
| Water Content (lb./yd$^3$) | 276 | 266 | 280 | 266 | 275.5 | 280 | 280 | 285 |
| Water /Binder | 0.3 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.3 |
| ADVA 170 (fl z./cwt) | 0 | 0 | 0 | 0 | 0 | 5 | 3 | 0 |
| ADVA 530 (fl oz./cwt) | 10 | 15 | 16 | 18 | 18 | 6 | 9 | 12 |
| Fresh Concrete Properties | | | | | | | | |
| Slump flow (in.) | 24 | 21 | 23 | 23.5 | 25.5 | 29 | 27.5 | 26 |
| T 20 (s) | 5 | 8 | 5 | 4 | 4 | 4 | 9 | 6.5 |
| Time of max spread (s) | 20 | 20 | 29 | 30 | 32 | 30 | 60 | 55 |
| Bleed water | no | no | no | yes | yes | yes | yes | yes |
| Segregation observed | no | no | no | no | no | yes | no | no |
| VSI | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 3 | 1 | 1 |
| Unit weight | 150.2 | 153.1 | - | - | - | - | - | - |
| Air Content (%) | 2.5 | 1.8 | 1.4 | 1.4 | 1.1 | - | - | - |
| Compressive strength (psi) | | | | | | | | |
| 1-day strength (psi) | 6150 | 6820 | 6550 | 6480 | 5730 | 5550 | 5820 | - |
| 7-day strength (psi) | 9700 | 11280 | 10340 | 10280 | 10190 | 9790 | 9630 | - |
| 28-day strength (psi) | 11770 | 11780 | 12090 | 11540 | 11290 | 10480 | 10890 | - |

The fourth series of SCC mixtures are shown below in Table 5. Since many mixtures of the third series had acceptable slump flows and the $T_{20}$ times, the J-ring was used in this series to test the blockage resistance. For these mixtures the w:b and cement content was held constant at 0.30 and 950 lb. /yd$^3$, respectively, except for Mixture 31. ADVA 170 was used to attain the desired flow of 26 inches and a $T_{20}$ less than 5 seconds. However, since ADVA 170 reduces both the yield stress and viscosity, there is a greater possibility of segregation and bleeding. Since ADVA 555 contains a VMA, it was used to control the bleeding and improve the segregation resistance.

Most of the mixtures in Series 4 had flows near the targeted value of 26 inches and a VSI less than one. Also, the 1-day strengths were approximately 6000 psi. Additionally, there was no bleeding or segregation for the mixtures. However, when the J-ring test was used, it showed some blockage. Most of the mixtures had $\Delta h$ greater than 0.5 in.

Therefore, the coarse aggregate content was reduced to 1300 lb. /yd$^3$ in order to overcome the blockage issue.

Based on the results of the flows and $T_{20}$, as the ADVA 555 dosage increased, the viscosity also increased. For the remaining mixtures, the ADVA 555 dosage never exceeded 2 fl oz. /cwt. For the mixtures tested, this dosage rate was sufficient in controlling bleeding.

All mixtures from the fourth series had satisfactory flows and viscosity, but there were blockage issues. The mixture proportions remained almost constant for these mixtures. The coarse aggregate content varied from 1350 to 1400 lb. /yd$^3$, and the dosage rate of ADVA 170 ranged from 11 to 12 fl oz. /cwt.

Table 5 SCC Mixtures and Properties (Series 4).

| Materials | Mix Proportions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
| Cement (lb./yd$^3$) | 950 | 950 | 950 | 950 | 950 | 950 | 950 | 930 | 950 | 950 |
| Coarse Agg. (lb./yd$^3$) | 1400 | 1400 | 1400 | 1300 | 1300 | 1300 | 1300 | 1300 | 1350 | 1400 |
| Fine Agg. (lb./yd$^3$) | 1425 | 1425 | 1425 | 1523 | 1523 | 1523 | 1523 | 1531 | 1474 | 1425 |
| Water Content (lb./yd$^3$) | 285 | 285 | 285 | 285 | 285 | 285 | 285 | 288.3 | 285 | 285 |
| Water /Binder | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.31 | 0.3 | 0.3 |
| ADVA 170 (fl oz./cwt) | 4 | 6.5 | 11 | 9 | 9 | 10.5 | 11 | 10 | 10 | 10 |
| ADVA 555 (fl oz./cwt) | 8 | 4 | 2 | 3 | 6 | 2 | 2 | 2 | 1 | 1 |
| Fresh Concrete Properties | | | | | | | | | | |
| Slump flow (in.) | 23.5 | 19 | 27 | 25 | 19 | 26 | 27.5 | 29 | 26 | 19 |
| T 20 (s) | 5.5 | - | 7.5 | 5.5 | - | 4 | 3.6 | 3 | 3 | - |
| Time of max spread (s) | 30 | 35 | 53 | 33 | - | 30 | 30 | 35 | 30 | 20 |
| J-ring spread | 20 | - | 21 | 21.5 | - | 23 | 23.5 | 23 | 27 | - |
| $\Delta h^*$ | 1 | - | 1 | 0.8 | - | 0.9 | 0.55 | 0.5 | 0.3 | - |
| Bleed water | no | no | no | no | no | no | no | no | no | no |
| Segregation observed | no | no | no | no | no | no | no | no | no | no |
| VSI | 0.5 | 1 | 0 | 0 | 1 | 0 | 0.5 | 0.5 | 0.5 | 0.5 |
| Unit weight | - | - | - | - | - | - | - | - | - | - |
| Air Content (%) | - | - | - | - | - | - | - | - | - | - |
| Compressive strength (psi) | | | | | | | | | | |
| 1-day strength (psi) | 6650 | - | 6790 | 6390 | - | 6040 | 5680 | 5720 | 5780 | - |
| 7-day strength (psi) | 11890 | - | 13210 | 12800 | - | 12810 | 13440 | 12140 | 12130 | - |
| 28-day strength (psi) | 13830 | - | 14610 | 14310 | - | 14710 | 14830 | 13970 | 13790 | - |

$^*\Delta h$: height difference between concrete inside and outside the J-ring.

Figure 2 Blockage of Mixture # 29

The final series (Series 5) of SCC mixtures are shown in Table 6. There were no changes in binder content, w:b, but there were minor changes in the coarse aggregate content for this final set of ten mixtures. Admixture dosage rates were the main focus of Series 5. Mixtures 43 and 44 had good flows, but there was some bleed water. Because of the presence of bleed water, the dosage rate of ADVA 555 was increased for the remaining mixtures. As with some of the mixtures from Series 4, there were some mixtures that were identical, but they performed differently. For example, 11 fl oz. /cwt of ADVA 170 produced good flows in Mixture # 43; while Mixtures #39, 40, 42 had slump flows less than 21 inches.

The final mixture (Mixture 49), which was identical to Mixture 47 and was batched at 6 $ft^3$, met the performance requirements of the research program. The spread was 28.5 in, the $T_{20}$ was 3 s., and there was no blockage when testing with the J-ring (the height difference was 0.2 in.). In addition, slump flows were measured out to 50 minutes and the final flow (at 50 minutes) was 24 in. This showed there was not a rapid slump loss problem for this mixture. The 1-day strength was 5900 psi and the 7-day strength was 12200 psi. With this mixture, six precast/prestressed beams were cast.

Table 6 SCC Mixtures and Properties (Series 5).

| Materials | Mix proportions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 39 | 40 | 41* | 42 | 43 | 44 | 45 | 46 | 47 | 48 |
| Cement (lb./yd$^3$) | 950 | 950 | 950 | 950 | 950 | 950 | 950 | 950 | 950 | 950 |
| Coarse Agg. (lb./yd$^3$) | 1400 | 1400 | 1350 | 1350 | 1350 | 1350 | 1350 | 1350 | 1350 | 1350 |
| Fine Agg. (lb./yd$^3$) | 1425 | 1425 | 1474 | 1474 | 1474 | 1474 | 1474 | 1474 | 1474 | 1474 |
| Water Content (lb./yd$^3$) | 285 | 285 | 285 | 285 | 285 | 285 | 285 | 285 | 285 | 285 |
| Water /Binder | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| ADVA 170 (fl oz./ cwt) | 11 | 11 | 7 | 11.5 | 11 | 12 | 11 | 11.5 | 11.5 | 11 |
| ADVA 555 (fl oz./ cwt) | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 1.5 | 2 | 1.5 |
| Fresh Concrete Properties | | | | | | | | | | |
| Slump flow (in.) | 21 | 20 | 29 | 19 | 28 | 28 | 23 | 26.5 | 31 | 27 |
| T 20 (s) | 5.5 | 17 | 3.5 | - | 4 | 5 | 4 | 3 | - | 3.5 |
| Time of max spread (s) | 20 | - | 29 | - | 39 | 43 | 26 | 33 | - | 31 |
| J-ring spread | - | - | - | - | 24 | 26.5 | 21.5 | 24 | - | 23 |
| $\Delta$h | - | - | - | - | 0.8 | 1 | 1 | 0.5 | - | 0.6 |
| Bleed water | no | no | yes | no | a little | a little | no | no | yes | no |
| Segregation observed | no | no | yes | no | no | no | no | no | yes | no |
| VSI | 0 | 1 | 2 | - | 1 | 1 | 0.5 | 0.5 | 3 | 0.5 |
| Unit weight | - | - | - | - | - | 152.9 | 151 | 152.1 | - | 152.9 |
| Air Content (%) | - | - | - | - | 0.6 | 0.4 | 1.8 | 1.6 | - | 1.3 |
| Compressive strength (psi) | | | | | | | | | | |
| 1-day strength (psi) | 5560 | - | - | - | 5980 | 6380 | 5540 | 5930 | - | 6320 |
| 7-day strength (psi) | - | - | - | - | 12100 | 11750 | 12360 | 12480 | - | 12660 |
| 28-day strength (psi) | - | - | - | - | 13990 | 13150 | 13700 | 14,280 | - | 14360 |

* 4 fl oz. / cwt of ADVA 530 were used.

Finally, six prestressed beams were cast using Mixture # 48, and 6.0 ft$^3$ were batched at a time due to the limited volume of the mixer. The admixture dosage was different for each batch due to different aggregate moisture contents and fresh concrete temperature. Specifically, incremental adjustments to the admixture dosage rate were made for each batch until the flow was satisfactory.

## CONCLUSIONS

The goal of this project was to develop high strength SCC that can be applied to precast/prestressed applications. A high strength, SCC mixture with a w:b of 0.30 was developed. The mixture was flowable and resistant to segregation in addition to having a

1-day strength of 5930 psi and a 28-day strength of 14,280 psi. After 49 batches, several conclusions have been drawn for the materials and mixtures developed in this research program:

- Choosing a w:b should be the first step to attain the strength and then followed by steps to attain the desired fresh properties such as slump flow, $T_{20}$.
- Coarse aggregate content should be low (1400 lb. /yd$^3$ or less) and the maximum coarse aggregate size should be small as possible to increase the flowability and reduce the potential of blockage.
- Multiple trial batches should be used to determine the best dosage of admixtures. If the admixture dosage rates are significantly higher than the manufacturer’s recommended dosage rate, the water content should be increased by increasing binder content and keeping w:b constant.
- High dosages of HRWR can improve flow, but low w:b mixtures may still be too viscous. In addition, overdosing HRWR could lead to segregation. If the flow is adequate but the mixture is still too viscous, the water content should be increased.
- The water content is very important because it controls the viscosity of the mixture. High water content will lead to a greater possibility of segregation while low water content will make the mixture too viscous.
- The research team experienced difficulty using silica fume in low w:b SCC along with compatibility issues with the VMA
- $T_{20}$ is an important test for SCC. For the mixtures tested, the $T_{20}$ of 3 to 5 seconds worked well, and problems with blockage occurred at $T_{20}$ times outside this range.
- Using high admixture dosage rates (more then 1.5 to 2 times the manufacturers recommended rates) should be avoided if possible, because overdosing can result in increased setting times, segregation, or bleeding.
- When developing an SCC mixture proportion, producing SCC should begin with a properly proportioned concrete mixture proportion and the VMAs should be used only for the “fine tuning” of the mixture (to obtain the desired fresh concrete properties).
- The optimum dosage of HRWR is sensitive to any changes in moisture contents of the aggregates and concrete temperature; therefore, adjustments should be considered.

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