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# Development of Self-Consolidating Concrete for Prestressed Bridge Beams

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Synopsis: Sixteen self-consolidating concrete (SCC) mixtures were developed for use in precast, prestressed bridge beams in Texas. The mixtures featured two different sets of aggregates—namely with river gravel or crushed limestone coarse aggregate—and varied in sand-aggregate ratio, paste volume, and paste composition. The 16-hour compressive strengths (release strengths) ranged from 4,500 to 10,500 psi (30 to 70 MPa) depending on the mixture proportions and curing temperature history. The 28-day compressive strengths ranged from 11,000 to nearly 15,000 psi (75 to 100 MPa). The SCC mixtures were developed to achieve the necessary release strengths while balancing the requirements for adequate workability and durability.

This paper discusses the need for higher paste volumes and sand-aggregate ratios to achieve SCC workability requirements and the implications for hardened properties. Semi-adiabatic and isothermal calorimetry measurements performed on concrete and paste specimens, respectively, and compressive strength measurements indicated that although the SCC mixtures exhibited slightly delayed setting times in some cases, they generated heat at a faster rate, generated more total heat, and developed higher 28-day strength for a given release strength. Compared to conventional mixtures with the same release strength, the SCC mixtures exhibited unchanged or slightly reduced shrinkage except when one specific admixture was used.

Keywords: calorimetry; mixture proportioning; prestressed concrete; self-consolidating concrete; shrinkage

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## INTRODUCTION

The ability of self-consolidating concrete (SCC) to flow under its own mass, pass through congested reinforcement, and resist segregation can result in substantial benefits for producers and purchasers of precast, prestressed concrete bridge beams. The modifications to mixture proportions required to achieve these workability characteristics may have consequential implications for hardened properties. Potential modifications to mixture proportions include higher paste volume, increased sand-aggregate ratio (S/A), and reduced maximum aggregate size. For prestressed concrete bridge beams, the compressive strength required for the release of tension in strands, typically needed within 16 hours, is crucial so that precasters can re-use their beds with minimal turn-over time. Long-term strength, stiffness, shrinkage, and durability are also important. A Texas Department of Transportation (TxDOT)-sponsored research project was conducted at the University of Texas at Austin (workability and early-age properties) and Texas A&M University (longer-term properties) to evaluate the suitability of SCC for prestressed bridge beams in Texas. This paper discusses the tradeoffs associated with proportioning SCC mixtures to achieve the required workability and hardened properties needed for prestressed concrete bridge beams and presents test results for early-age compressive strength development, heat generation (calorimetry), and shrinkage. Longer-term properties will be reported by the Texas A&M University researchers.

## RESEARCH SIGNIFICANCE

To implement SCC in prestressed concrete applications, mixture proportions must be developed that are economical, achieve high early-age compressive strengths, and exhibit adequate workability and long-term hardened properties. Although hardened property requirements do not limit the design of SCC mixtures in some cases, both workability and hardened property requirements controlled the design of the mixtures in the research described herein. This paper illustrates why higher paste volumes and S/As are needed for SCC mixtures in prestressed bridge beams in Texas and discusses the implications.

## DEVELOPMENT OF MIXTURE PROPORTIONS

### Requirements

SCC mixtures were proportioned for workability and hardened properties. For workability, mixtures were designed for filing ability, passing ability, and segregation resistance[1]. The target workability properties are shown in Table 1. For hardened properties, mixtures were designed for 16-hour compressive strength. Because early-age strength development is highly dependent on temperature, mixtures were cured at a range of imposed temperature histories selected to be representative of beams cured in Texas weather conditions throughout the year. These temperature histories, which are shown in Figure 1, vary in the pre-set time (time from casting until temperature increases) and maximum temperature. Each mixture was identified in terms of its nominal 16-hour strength, which was achieved with an 8-hour pre-set time and 120°F (49°C) maximum temperature. Mixtures were developed with nominal 16-hour compressive strengths of 5,000 and 7,000 psi (35 and 48 MPa). The mixtures varied in S/A, paste volume, and paste composition to evaluate the effects of these parameters on hardened properties.

The 2004 TxDOT specifications[2], which do not address SCC, were also considered. To meet TxDOT specifications, mixtures must contain no more than 700 lb/yd$^3$ (415 kg/m$^3$) of cementitious materials unless otherwise specified or approved. Mixtures must meet one of 8 options (7 prescriptive and 1 performance) intended to mitigate alkali-silica reaction. For this research, the options to replace 20-35% of cement with Class F fly ash and to limit the total alkali content to less than 4 lb/yd$^3$ (2.4 kg/m$^3$) were used. The specifications limit the maximum internal curing temperature to 170°F (77°C) for mixtures where certain specified combinations of supplementary cementitious materials (SCMs) are used and to 150°F (66°C) in other cases. Concrete for prestressed bridge beams in Texas is not typically air-entrained.

Materials

Materials were selected to be representative of those used by precasters in Texas. Two aggregate sets—a crushed limestone coarse aggregate with a natural sand and a river gravel with a separate natural sand—were used (Table 2). The maximum size of both coarse aggregates was ¾ inch (19 mm). A Type III cement and Class F fly ash were used (Table 3). Chemical admixtures included a retarder, a viscosity-modifying admixture (VMA), and an experimental admixture that extended workability retention and accelerated strength development. Two polycarboxylate-based high-range water-reducing admixtures (HRWRAs) were used (HRWRA-01 for SCC mixtures and HRWRA-02 for conventional concrete mixtures).

Methodology

Sixteen SCC mixtures were developed to cover the range of mixture proportions likely to be used for prestressed bridge beams in Texas (Figure 2). For each aggregate set, 5 mixtures were developed for a nominal 16-hour compressive strength level of 5,000 psi (35 MPa) and 3 mixtures for a nominal 16-hour compressive strength level of 7,000 psi (48 MPa). For the 5,000 psi mixtures, the S/A varied from 0.40 to 0.50. Three mixtures varied only in S/A (0.40, 0.45, and 0.50) to allow an independent comparison of the effects of S/A. Maintaining a constant paste volume for these three mixtures, however, resulted in paste volumes that were higher than necessary for the mixtures with S/As of 0.45 and 0.50. These higher paste volumes were needed so that all three mixtures would exhibit adequate workability while varying only in S/A. Therefore, separate mixtures were developed with S/As of 0.45 and 0.50 with optimized paste volumes. For the 7,000 psi nominal strength level, three mixtures were developed for each aggregate set varying only in S/A (0.42, 0.46, and 0.50). The SCC mixtures were compared to 4 conventionally placed concrete mixtures (one mixture at each nominal strength level for each aggregate set).

The ICAR SCC mixture proportioning procedure[3] was used to develop the final mixture proportions. In this procedure, concrete is represented as a suspension of aggregates in paste, as depicted schematically in Figure 3. This representation provides a consistent, fundamental framework for evaluating mixtures. To proportion mixtures, the combined aggregates, paste volume, and paste composition are selected to achieve the desired workability and hardened properties. These three steps are summarized in Table 4 and described in general terms in the following three paragraphs.

First, the combined aggregates are selected on the basis of maximum size; grading; and shape, angularity, and texture. These factors are selected to minimize the voids content between aggregates and reduce interparticle friction between aggregates while the maximum size and grading are limited for segregation resistance and passing ability. Although a wide range of aggregates can be used in SCC, minimizing the voids content between aggregates and improving the shape and angularity reduces the required paste volume, resulting in greater economy and improved hardened properties[3].

Second, the required minimum paste volume is selected separately for filling ability and passing ability. The minimum paste volume is primarily a function of the aggregate characteristics. Without the minimum paste volume, concrete would not exhibit adequate SCC workability regardless of the paste composition. For filling ability, sufficient paste volume must be provided to fill the voids between compacted aggregates and to lubricate aggregates by providing spacing between aggregates (Figure 3). If only sufficient paste volume were provided to fill the voids between aggregates, the substantial interparticle friction between aggregates would prohibit flow. An equation was developed in the ICAR procedure to calculate an estimate of the paste volume for filling ability as a function of the voids in compacted aggregates and the aggregate shape and angularity. Selecting well-shaped and well-graded aggregates reduces the voids in compacted aggregates (increased packing density), which reduces the needed paste volume. Additionally, aggregates that are equidimensional and well rounded reduce interparticle friction, which reduces the paste needed to separate aggregates. For passing ability, increasing the paste volume reduces the volume of aggregates that must pass through congested reinforcement and reduces the interparticle friction between aggregates. The amount of paste volume for passing ability can be reduced by using a smaller maximum aggregate size, reducing the coarseness of the grading, or selected equidimensional, well-rounded aggregates. The minimum paste volume for passing ability can be determined experimentally based on J-Ring blocking by varying the paste volume for a given aggregate blend. The minimum paste volume is selected as the greater of the minimum paste volume for filling ability or passing ability. This amount of paste volume can be increased for robustness with respect to changes in aggregate properties[3].

Third, the composition of the paste—namely the blend of powders and the relative amounts of powder, water, and air—is selected to achieve proper workability and hardened properties. The paste composition step is where the distinction between powder type- and VMA-type SCC is made[4]. Powder type-SCC consists of high powder contents and low water-powder ratios (typically <0.40) whereas VMA-type SCC consists of lower powder contents, higher w/p (typically >0.45), and VMA. The use of VMA is not restricted to mixtures with these higher w/p. In establishing the paste composition, the powder blend and water-powder ratio are set to achieve the desired concrete rheology. The powder blend and water-cementitious materials ratio are set to achieve the desired long-term hardened properties. When powders with low reactivity at early ages are used—such as Class F fly ash and some mineral fillers—the water-cement ratio is set to achieve the desired early-age hardened properties. Generally, the cement content should be minimized to achieve hardened properties and other powders added to comprise the remainder of the powder volume and to achieve the desired rheology. To maintain constant concrete rheology as the paste volume or aggregates are changed, the paste composition must be adjusted. For all mixtures, the HRWRA is adjusted to achieve the required slump flow, which is related to yield stress[3]. The near-zero yield stress for SCC is the main workability difference between SCC and conventionally placed concrete. The plastic viscosity—which is approximately correlated to $T_{50}$ and is a function of aggregates, paste volume, and paste composition[3]—must not be too low (poor stability) or too high (poor placeability).

### Nominal 5,000 psi (35 MPa) Mixtures

The ICAR mixture proportioning procedure is demonstrated in the following paragraphs for the nominal 5,000 psi (35 MPa) 16-hour compressive strength mixtures.

Step 1: Aggregates—Each aggregate set was used at S/As of 0.40 to 0.50. The gradings at these S/As were considered suitable for SCC[3]. The voids contents for all aggregate combinations were determined as shown in Table 5.

Step 2: Paste Volume—The minimum paste volumes for each S/A were determined by experimentally evaluating filling ability and passing ability at various paste volumes in reference to the requirements in Table 1. Due to the congested reinforcement in the prestressed beams, passing ability controlled the selection of minimum paste volume (Table 5). The effect of paste volume on passing ability is illustrated in Figure 4. Decreasing the S/A required more paste volume due to the increased amount of coarse particles. Although the two aggregate sets had similar compacted voids content, the paste volumes required for both filling and passing abilities were higher for the crushed limestone coarse aggregate set due to the greater angularity of the crushed limestone. The minimum paste volumes determined for passing ability were increased by 1% to ensure robustness with respect to changes in aggregate properties.

Step 3: Paste Composition—The paste composition was optimized for each aggregate set and paste volume. A retarder was used in all mixtures to ensure workability retention. The w/c for a nominal 5,000 psi compressive strength, with retarder, was determined to be 0.41 for the river gravel aggregate set and 0.45 for the crushed limestone aggregate set (Figure 5). With the w/c established, the w/p (equal to w/cm in this case) and fly ash rate were adjusted for each paste volume to achieve proper concrete rheology and fill the required paste volume. In all cases, the HRWRA dosage was adjusted to reach the desired slump flow.

The final mixture proportions are shown in Table 6 and Table 7 for the river gravel and crushed limestone aggregate sets, respectively. The main challenge in developing the mixture proportions was the need to achieve the following three objectives simultaneously: passing ability, early-age compressive strength, and maximum cementitious materials content. The passing ability requirements dictated a minimum paste volume so that SCC would flow through the congested reinforcement typical of prestressed concrete bridge beams. The minimum strength requirements dictated low w/c and—in order for sufficient paste volume and rheology—low w/p and high powder contents. Although fly ash could have been eliminated, resulting in higher w/p and lower powder content, the cement content would still have been too high. Consequentially, it was not possible to keep the cementitious materials content less than 700 lb/yd$^3$ (415 kg/m$^3$). Had the cementitious materials content been kept below this limit, the paste volume would have been too low for workability, the w/c too high for early-age compressive strength, or both. Ensuring passing ability and 16-hour compressive strength was determined to be more important than limiting total cementitious materials content. Despite the high cementitious materials content, the use of fly ash increased economy, reduced heat generation, and enhanced durability.

Nominal 7,000 psi (48 MPa) Mixtures

For mixtures at a nominal 7,000 psi (48 MPa) 16-hour compressive strength level, the challenge of achieving passing ability, early-age compressive strength, and maximum cementitious materials content simultaneously was magnified. For example, with the river gravel aggregate set, the maximum w/c was determined to be 0.31 to achieve the nominal strength of 7,000 psi (with use of retarder for workability retention). Table 8 shows several options that were considered for an S/A of 0.42. In the first option, the cement content was limited to 700 lb/yd$^3$ (415 kg/m$^3$); however, the w/c was too high. In the second option, the w/c was reduced to 0.31; however, the cement content was too high. In the third option, 20% fly ash was used to reduce the cement content and the w/p was reduced to ensure the proper w/c; however, the water content was too low for workability, resulting in extremely viscous concrete.

Because none of these three mixtures was viable, a new experimental admixture was considered. This experimental admixture extends workability retention and accelerates strength gain. The extended workability retention allowed the retarder to be removed. The lack of retarder, combined with the accelerated strength gain associated with the experimental admixture, allowed the w/c to be increased, as shown in Table 8. A low dosage of VMA was used in the mixtures with S/As of 0.42 to ensure stability. The experimental admixture was used in all mixtures designed for a nominal 16-hour compressive strength level of 7,000 psi (48 MPa), as listed in Table 6 and Table 7.

Discussion

SCC is defined in terms of its workability. Changes in hardened properties associated with SCC are primarily attributable to specific changes in mixture proportions required to achieve workability characteristics, not to the workability characteristics themselves[3]. Therefore, hardened properties should be evaluated on a case-by-case basis in terms of specific changes to mixture proportions instead of associating certain hardened properties with SCC in general. In addition, the improved consolidation and lack of vibration associated with SCC may result in improved hardened properties[3]. For the mixtures described in this paper, the major changes in mixture proportions were increased paste volume, increased S/A, and use of fly ash. The maximum aggregate size was unchanged.

Paste volume—SCC must have higher paste volume than conventionally placed concrete to ensure filling ability and passing ability. For prestressed concrete bridge beams and other highly congested members, the selection of minimum paste volume is typically controlled by passing ability. Depending on the aggregate, paste volumes of 28-40% are typical for SCC[3]. Higher paste volume does not necessarily require higher cement or cementitious materials content. Higher paste volume has been associated with increased shrinkage[1,3,5,6,7], reduced modulus of elasticity[1,3,8], and increased cost. Although increasing the paste volume may reduce modulus of elasticity, changing the stiffness of the aggregates can have a greater effect[3]. The paste volume required for passing ability is primarily a function of the aggregate characteristics and can be reduced by reducing the maximum size, reducing the coarseness of the combined grading, and improving the shape and angularity of both the fine and coarse aggregates[3]. These changes can also affect hardened properties themselves and should be evaluated accordingly. To a lesser extent, passing ability can be increased by reducing the paste yield stress and plastic viscosity[3].

S/A—The S/A relates to aggregate grading, whereas workability depends on aggregate grading and shape and angularity characteristics. Increasing the S/A can improve passing ability and segregation resistance while decreasing the S/A can—to a certain point—result in improved filling ability[3]. When changing the S/A, it is important to consider the individual properties of the sand and coarse aggregates. For instance, reducing the coarseness of a grading (higher S/A) is known to reduce modulus of elasticity[1,8]. If the coarse aggregate is of much lower stiffness than the sand, however, an increase in S/A may result in increased modulus of elasticity[3]. There are typically optimal S/As associated with packing density and filling ability[3]. The actual optimal S/A for a given aggregate set depends on the grading, shape, and angularity of the individual fine and coarse aggregates[3].

Maximum aggregate size—The maximum aggregate size in SCC is limited by passing ability and segregation resistance. Increasing the maximum size improves filling ability to the extent it improves the combined aggregate grading[3]. The maximum aggregate size is limited by clear spacings, such as between reinforcement. However, further reducing the maximum aggregate size can reduce the paste volume needed for passing ability. In general, the largest maximum aggregate size should be used subject to limits on passing ability and segregation resistance. Increasing the maximum aggregate size is known to increase modulus of elasticity[8] and reduce compressive strength[9].

Fly ash—SCC often incorporates fly ash and other SCMs to achieve adequate paste volume and w/p for workability. Fly ash also reduces cost, reduces heat generation, and improves durability[3]. In the SCC mixtures described in this paper, the cement contents were approximately the same or slightly increased relative to the comparable conventional control mixtures; however, the water contents and fly ash contents were increased to achieve adequate paste volume and w/p for workability.

### Calorimetry and Early-Age Compressive Strength

Isothermal and semi-adiabatic calorimeter measurements were used to evaluate the heat generation of paste and concrete mixtures, respectively. Isothermal calorimeter measurements were made with an 8-channel isothermal heat conduction calorimeter with 20 ml maximum specimen size (Thermometric 3114 TAM Air). Pastes were mixed in a blender and placed in the calorimeter, which was maintained at constant temperatures ranging from 41 to 140°F (5 to 60°C)[10]. The semi-adiabatic calorimeter consisted of a 6x12-inch (152x305-mm) cylindrical concrete specimen positioned inside an insulated, 55-gallon (208-liter) steel drum. Measurements were made of the concrete temperature, heat loss through the calorimeter walls, and ambient temperature surrounding the calorimeter. These measurements were used to calculate the adiabatic temperature rise[11]. The concrete mixtures tested had fresh temperatures of 75 to 81°F (24 to 27°C) and were measured in the semi-adiabatic calorimeter for 7 days.

Figure 6 shows isothermal calorimetry results for 5 pastes tested at 73.4°F (23°C). The addition of fly ash delayed the start of heat evolution and reduced the peak rate of heat evolution. This reduction was expected due to the lack of reactivity of low calcium fly ashes at early ages. HRWRA delayed the start of heat evolution but increased the maximum rate of heat evolution. This behavior was expected because HRWRAs delay initial setting but result in improved dispersion and more efficient hydration[12,13]. When combined, fly ash and HRWRA resulted in delayed start of heat evolution and increased peak rate of heat evolution. The addition of retarder to the paste with fly ash and HRWRA further delayed the start of heat evolution and slightly reduced the peak rate of heat evolution. In terms of total heat evolved, the mixtures with fly ash evolved less heat per mass of cementitious materials at all ages measured. However, when compared per mass of cement only, as shown in Figure 7, the mixtures with fly ash evolved heat at a faster rate per cement mass after a certain time (6-8 hours) and generated more total heat per cement mass, reflecting the eventual contribution of fly ash to hydration. As mentioned earlier, the SCC mixtures had similar or only slightly higher total cement contents as the comparable conventional mixtures.

Isothermal calorimetry was used to determine activation energy, which reflects the sensitivity of hydration to temperature. Eight pastes, varying in fly ash rate and admixture type and dosage, were tested to represent the range of paste compositions in the concrete mixtures. As shown in Table 9, the activation energies of the pastes representing the SCC mixtures varied from 34 to 37 kJ/mol, which were similar to the 35 kJ/mol determined for the two pastes representing conventionally placed concrete mixtures. The activation energy of the paste with the experimental admixture, however, was significantly reduced to 24.6 kJ/mol. Therefore, the amount of heat generated in mixtures with the experimental admixture is expected to vary less with temperature changes.

Semi-adiabatic calorimeter results for 5 concrete mixtures are compared in Figure 8. For the 5,000 psi strength level, the SCC mixtures from both aggregate sets generated greater adiabatic temperature rise than the comparable conventional mixtures, which was likely due to the reduced w/c and improved dispersion and hydration from the HRWRA. The 7,000 psi mixture generated less heat than the 5,000 psi mixtures prior to 24 hours. Setting time and total adiabatic temperature rise after 40 hours are shown for all mixtures in Table 6 and Table 7. The data show that, for a given aggregate set, the setting times of the SCC mixtures at the nominal 5,000 psi strength level were delayed; however, these mixtures generated heat at a faster rate, generated more total heat, and developed higher 28-day compressive strengths. The same trends were true for the 7,000 psi mixtures; however, the setting times were not delayed.

The amount of heat generated is important because the curing temperature history significantly affects 16-hour compressive strength, as indicated in Figure 9 for two SCC mixtures. In addition, total heat generated should be minimized to prevent thermal cracking and delayed ettringite formation. Depending on the weather conditions and curing practices, the 16-hour compressive strength could vary from 4,500 to 8,100 psi (31 to 56 MPa) for mixture RG-5-50a and from 4,900 to 9,000 psi (34 to 62 MPa) for mixture RG-7-50. Figure 10 shows the compressive strength of 4 mixtures as a function of equivalent age. Similar strength versus maturity curves were developed for each mixture. These curves, along with knowledge of the amount of heat generated by the concrete mixtures, can be used to select curing conditions and mixture proportions based on expected ambient weather conditions in order to achieve the desired release strength.

### Shrinkage

Shrinkage was measured in accordance with ASTM C 157 with 3x3x11.25-inch (76x76x286-mm) specimens with 10-inch (255-mm) gage length. After casting, specimens were stored at 73°F (23°C) and 100% relative humidity for the first 16 hours. The specimens were then demolded, measured for initial length, and stored at 73°F (23°C) and 50% relative humidity for the remainder of the test. Drying was started at 16 hours to reflect field conditions. Autogenous shrinkage, which may be of concern given the low water-cement ratios, was not independently measured.

For the 5000 psi nominal strength level, shrinkage was unchanged for the river gravel mixtures (Figure 11) and slightly decreased for the crushed limestone mixtures (Figure 12) when compared to the conventional mixtures. At the 7,000 psi nominal strength level; however, the shrinkage increased for both aggregate sets compared to the conventional mixtures. This increase in shrinkage, which varied from 14 to 26%, was attributable to the experimental admixture as shown in Figure 11. Decreasing the S/A ratio reduced shrinkage in the crushed limestone aggregate set slightly but had no effect on the river gravel aggregate set. Decreasing the paste volume in mixtures RG-5-50a and LS-5-50a had no effect on shrinkage. Despite the lower paste volumes in RG-5-50a and LS-5-50a, the total water contents per unit volume were approximately the same as in the SCC mixtures with higher paste volume (RG-5-50a vs. RG-5-50; LS-5-50a vs. LS-5-50). For a given strength level and S/A, the mixtures with the crushed limestone aggregate set exhibited 10-30% higher shrinkage than the mixtures with the river gravel aggregate set, which was likely due to the reduced stiffness of the crushed limestone aggregates and possibly due to the higher paste volumes in the crushed limestone aggregate mixtures.

## CONCLUSIONS

SCC mixture proportions were developed to meet both workability and hardened property requirements for prestressed bridge beams. The mixtures varied in aggregate source, S/A, paste volume, and paste composition. Selecting SCC mixture proportions is an optimization process that requires consideration of the specific effects of each change in mixture proportions on workability and hardened properties. Requirements for workability and hardened properties imposed conflicting limits on mixture proportions. To provide a minimum paste volume for workability and a maximum w/c for 16-hour compressive strength, the total cementitious materials content was above the original maximum target of 700 $lb/yd^3$ (415 $kg/m^3$). The 16-hour compressive strength varied significantly with the curing temperature history; therefore, strength-maturity relationships were developed that can be used to select mixture proportions and curing practices based on required 16-hour compressive strength and expected weather conditions. Calorimetry and early-age compressive strength measurements indicated that although the setting times of the SCC mixtures were delayed at the nominal 5,000 psi (35 MPa) compressive strength level, the SCC mixtures generated heat at a faster rate, generated more total heat, and developed higher 28-day compressive strengths. For the nominal 5,000 psi compressive strength level, shrinkage was unchanged for the river gravel aggregate set and slightly reduced for the crushed limestone aggregate set relative to the comparable conventional concrete mixtures. For the nominal 7,000 psi (48 MPa) compressive strength level, the shrinkage was increased 14-26% relative to the conventional concrete mixtures, which was due to the effect of the experimental admixture.

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## REFERENCES

1. EFNARC (2005). “European Guidelines for Self-Compacting Concrete,” www.efnarc.org

2. Texas Department of Transportation (2004). “Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges,” June 1, 2004.

3. Koehler, E.P., and Fowler, D.W. (2007). “Aggregates in Self-Consolidating Concrete,” (Report 108.1), International Center for Aggregates Research, Austin, TX.

4. Japanese Society of Civil Engineers (1999). “Recommendations for Self-Compacting Concrete,” (Concrete Engineering Series 31). ed. T. Uomoto and K. Ozawa.

5. Bissonnette, B., Pascale, P., and Pigeon, M. (1999). “Influence of key parameters on drying shrinkage of cementitious materials,” *Cement and Concrete Res.*, 29, pp. 1655-1662.

6. Hammer, T.A. (2003). “Cracking susceptibility due to volume changes of self-compacting concrete (SCC),” *Third International Symposium on Self-Consolidating Concrete*, Reykjavik, Iceland, pp. 553-557.

7. Roziere, E., Turcry, P., Loukili, A., and Cussigh, F. (2005). “Influence of paste volume, addition content and addition type on shrinkage cracking of self-compacting concrete,” *Proceedings of SCC 2005*, ACBM, Chicago, IL.

8. Ahmad, S.H., and Shah, S.P. (1985). “Structural Properties of High Strength Concrete and its Implications for Precast Prestressed Concrete,” *PCI J.*, 30(6), pp. 92-119.

9. ACI Committee 363. (1992). “State-of-the-Art Report on High Strength Concrete,” (ACI 363R-92). American Concrete Institute, Farmington Hills MI.

10. Poole, J.L., Riding, K.A., Folliard, K.J., Juenger, M.C.G., and Schindler, A.K. (2007). “Methods for Calculating Activation Energy for Portland Cement,” *ACI Materials Journal*, 104(1), pp. 303-311.

11. Schindler, A.K. (2002). “Concrete Hydration, Temperature Development, and Setting at Early Ages,” Ph.D. Dissertation, The University of Texas at Austin.

12. Jeknavorian, A.A., Jardine, L., Ou, C.C., Koyata, H., and Folliard, K. (2003). “Interaction of Superplasticizers with Clay-Bearing Aggregates,” *Seventh CANMET/ACI International Symposium on Superplasticizers and other Chemical Admixtures in Concrete*, Malhotra, V.M., Ed., pp. 143-159.

13. Bury, M.A., and Christensen, B.J. (2002). “Role of innovative chemical admixtures in producing self-consolidating concrete,” *First North American Conference on the Design and Use of Self-Consolidating Concrete*, ACBM, Chicago, IL.

**Table 1: Target Workability Properties**

| Property | Test Method | Target Properties |
|---|---|---|
| Filling Ability | Slump Flow (ASTM C 1611, inverted cone) | Achieve a slump flow of 28-30 inches (710-760 mm) with VSI$\leq$1.0 and 3 s$<T_{50}<$7 s; maintain a 23-inch (580-mm) slump flow 20 minutes after mixing. |
| Passing Ability | J-Ring (ASTM C 1621) | For an AASHTO Type IV beam, strands ~1.5-inch (40 mm) clear spacing. J-Ring $\Delta H<0.50$ inches (13 mm)* |
| Segregation Resistance | Column Segregation (ASTM C 1610) | Exhibit minimal segregation and top bar effect. Static segregation$\leq$15%. |

*In the J-Ring test, the difference in concrete height between the inside and outside of ring has been found to be a better indication of passing ability than the difference in slump flow with and without J-Ring.

**Table 2: Aggregate Characteristics**

| | | River Gravel Set | | Crushed Limestone Set | |
|---|---|---|---|---|---|
| | | River Gravel | Natural Sand A | Crushed Limestone | Natural Sand B |
| Specific Gravity | | 2.59 | 2.58 | 2.59 | 2.60 |
| Absorption Capacity, % | | 0.78 | 0.54 | 1.43 | 0.56 |
| Compacted Voids Content, % | | 34.2 | 33.6 | 41.4 | 32.4 |
| Gradation (% Passing) | 1” (25 mm) | 100.0 | | 100.0 | |
| | ¾” (19 mm) | 94.8 | | 95.1 | |
| | ½” (13 mm) | 64.3 | | 70.5 | |
| | $^3/_8$” (9.5 mm) | 40.4 | | 38.2 | |
| | #4 | 7.8 | 99.0 | 0.2 | 98.5 |
| | #8 | 2.2 | 86.5 | | 86.9 |
| | #16 | 1.5 | 73.8 | | 75.1 |
| | #30 | 1.2 | 49.3 | | 53.4 |
| | #50 | | 16.0 | | 20.9 |
| | #100 | | 3.8 | | 6.8 |
| | #200 | | 1.2 | | 1.8 |

**Table 3: Cement and Fly Ash Characteristics**

| Cement (Type III) | | Fly Ash (Class F) | |
|---|---|---|---|
| $C_3S$, % | 56.6 | Silicon Dioxide ($SiO_2$), % | 52.5 |
| $C_2S$, % | 16.3 | Aluminum Oxide ($Al_2O_3$), % | 21.8 |
| $C_3A$, % | 7.2 | Iron Oxide ($Fe_2O_3$), % | 4.9 |
| $C_4AF$, % | 10.3 | Calcium Oxide (CaO), % | 13.9 |
| Total Alkalies (as $Na_2O_{eq}$), % | 0.50 | Magnesium Oxide (MgO), % | 2.0 |
| Sulfur Trioxide ($SO_3$), % | 3.5 | Sulfur Trioxide ($SO_3$), % | 0.8 |
| Blaine Fineness, $m^2/kg$ | 539 | Available Alkalies (as $Na_2O_{eq}$), % | 0.24 |
| Specific Gravity | 3.15 | Specific Gravity | 2.33 |
| Loss on Ignition, % | 2.1 | Loss on Ignition, % | 1.05 |

**Table 4: Summary of ICAR SCC Mixture Proportioning Method**[3]

| Factor | Objective | Sub-Factors | Target |
|---|---|---|---|
| Aggregates | Minimize voids content (increase packing density) and reduce interparticle friction; limit grading as needed for passing ability and segregation resistance | Maximum Size | Reduce as needed for passing ability or segregation resistance |
| | | Grading | None universally optimal, best depends on aggregate and application |
| | | Shape, Angularity, Texture | Reduce interparticle friction |
| Paste Volume | Ensure filling and passing ability by filing voids in compacted aggregates and separating aggregates (lubrication); provide additional paste for robustness | Filling Ability | Fill voids and lubricate aggregates |
| | | Passing Ability | Reduce aggregate volume and interparticle friction |
| | | Robustness | Minimize effects of changes in materials and proportions |
| Paste Composition | Ensure adequate concrete rheology (yield stress, plastic viscosity, thixotropy) and hardened properties (strength, stiffness, durability), optimize economy | Water | w/p for rheology, w/c for early-age hardened properties, w/cm for long-term hardened properties |
| | | Powder | Total volume of powder and relative amounts of cement, SCMs, and mineral fillers for economy, strength, and durability |
| | | Air | As needed for durability |
| Adjust HRWRA to reach desired slump flow (yield stress for self-flow). Use VMA if necessary. | | | |

**Table 5: Minimum Paste Volume Requirements**

| S/A | River Gravel | | | Crushed Limestone | | |
|---|---|---|---|---|---|---|
| | Voids Content (%) | Req'd Paste Volume (%) | | Voids Content (%) | Req'd Paste Volume (%) | |
| | | Filling Ability | Passing Ability | | Filling Ability | Passing Ability |
| 0.40 | 23.9 | 32 | 36 | 23.9 | 38 | 41 |
| 0.45 | 23.6 | 30 | 34 | 23.3 | 36 | 38 |
| 0.50 | 23.2 | 28 | 32 | 22.7 | 35 | 36 |
| Larger minimum paste volume for filling ability or passing ability selected | | | | | | |

**Table 6: Final Proportions for River Gravel/Natural Sand Aggregate Set**

| | Conventional | | $f'_{ci}$=5,000 psi (35 MPa) | | | | | $f'_{ci}$=7,000 psi (48 MPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RG-5-C | RG-7-C | RG-5-50 | RG-5-45 | RG-5-40 | RG-5-50a | RG-5-45a | RG-7-50 | RG-7-46 | RG-7-42 |
| **Mixture Proportions** | | | | | | | | | | |
| Cement, lb/yd$^3$ (kg/m$^3$) | 625 (371) | 700 (415) | 633 (376) | 633 (376) | 633 (376) | 624 (370) | 646 (383) | 720 (427) | 720 (427) | 720 (427) |
| Fly Ash, lb/yd$^3$ (kg/m$^3$) | | | 298 (177) | 298 (177) | 298 (177) | 156 (93) | 239 (142) | 180 (107) | 180 (107) | 180 (107) |
| Coarse Aggregate, lb/yd$^3$ (kg/m$^3$) | 1937 (1149) | 1938 (1150) | 1372 (814) | 1509 (895) | 1646 (977) | 1459 (865) | 1532 (909) | 1401 (831) | 1513 (897) | 1625 (964) |
| Fine Aggregate, lb/yd$^3$ (kg/m$^3$) | 1234 (732) | 1235 (732) | 1366 (811) | 1230 (730) | 1093 (649) | 1453 (862) | 1249 (741) | 1395 (828) | 1284 (761) | 1172 (695) |
| Water, lb/yd$^3$ (kg/m$^3$) | 225 (133) | 200 (118) | 261 (155) | 261 (155) | 261 (155) | 257 (153) | 265 (157) | 243 (144) | 243 (144) | 243 (144) |
| HRWRA-01, oz/yd$^3$ (L/m$^3$) | | | 91 (3.5) | 83 (3.2) | 78 (3) | 83 (3.2) | 89 (3.4) | 118 (4.6) | 119 (4.6) | 115 (4.5) |
| HRWRA-02, oz/yd$^3$ (L/m$^3$) | 68 (2.6) | 117 (4.5) | | | | | | | | |
| Retarder, oz/yd$^3$ (L/m$^3$) | | | 25 (1) | 25 (1) | 25 (1) | 25 (1) | 26 (1) | | | |
| Experimental Admixture, oz/yd$^3$ (L/m$^3$) | | | | | | | | 578 (22.4) | 578 (22.4) | 578 (22.4) |
| VMA, oz/yd$^3$ (L/m$^3$) | | | | | | | | | | 4 (0.2) |
| **Mixture Indicies** | | | | | | | | | | |
| S/A | 0.39 | 0.39 | 0.5 | 0.45 | 0.4 | 0.5 | 0.45 | 0.5 | 0.46 | 0.42 |
| Coarse Agg. Vol., % | 44.4 | 44.4 | 31.4 | 34.6 | 37.7 | 33.4 | 35.1 | 32.1 | 34.7 | 37.2 |
| Paste Volume, % | 27.2 | 27.2 | 37.1 | 37.1 | 37.1 | 33.1 | 36.1 | 35.8 | 35.8 | 35.8 |
| w/cm | 0.36 | 0.285 | 0.28 | 0.28 | 0.28 | 0.33 | 0.3 | 0.27 | 0.27 | 0.27 |
| w/c | 0.36 | 0.285 | 0.412 | 0.412 | 0.412 | 0.413 | 0.411 | 0.338 | 0.338 | 0.338 |
| Fly Ash, % Mass | 0 | 0 | 32 | 32 | 32 | 20 | 27 | 20 | 20 | 20 |
| **Typical Fresh Properties** | | | | | | | | | | |
| Yield Stress, Pa | 294 | 195 | 6 | 44 | 16 | 11 | | 0 | 0 | 0 |
| Plastic Viscosity, Pa.s | 42 | 263 | 34 | 37 | 24 | 23 | | 56 | 66 | 51 |
| Slump, in. (mm) | 7.5 (190) | 7.25 (185) | | | | | | | | |
| Slump Flow, in. (mm) | | | 30 (760) | 28 (710) | 30 (760) | 28 (710) | | 28 (710) | 28 (710) | 27 (690) |
| $T_{50}$, s | | | 3.8 | 4.2 | 3.8 | 4.9 | | 8 | 7.4 | 7.4 |
| VSI | | | 0 | 0 | 0.5 | 0 | | 0 | 0 | 0 |
| J-Ring ΔH, in. (mm) | | | 0.13 (3) | 0.34 (9) | 0.19 (5) | 0 | | 0.25 (6) | 0.25 (6) | 0.44 (11) |
| Col. Segregation, % Static Seg. | | | 5 | 0 | 3 | 13 | | 7 | 0 | 7 |
| Initial Set, Hr:Min | 3:55 | 6:15 | 4:50 | 4:25 | 4:15 | 4:40 | | 5:50 | 4:50 | 4:15 |
| Final Set, Hr:Min | 5:10 | 8:50 | 6:10 | 5:35 | 5:35 | 5:50 | | 7:00 | 5:50 | 5:15 |
| Adiabatic Temp. Rise @ 40 hours, °C | 53.2 | 54.8 | 63.4 | 62.5 | 61.6 | 58.7 | | 61.0 | 62.3 | 59.8 |
| **Typical Hardened Properties** | | | | | | | | | | |
| 16-hr (8hr pre-set, 120F max) $f'_{ci}$, psi (MPa) | 5784 (39.9) | 6871 (47.4) | 5622 (38.8) | 6021 (41.5) | 5501 (37.9) | 5521 (38.1) | | 7108 (49) | 6986 (48.2) | 7296 (50.3) |
| 16-hr (4-hr pre-set, 170F max) $f'_{ci}$, psi (MPa) | 7099 (48.9) | 8456 (58.3) | 8705 (60) | | 8254 (56.9) | 8094 (55.8) | | 8767 (60.4) | | 9020 (62.2) |
| 28-day $f'_c$, psi (MPa) | 10854 (74.8) | 12706 (87.6) | 11733 (80.9) | 12062 (83.2) | 11774 (81.2) | 11223 (77.4) | | 13023 (89.8) | 13970 (96.3) | 14042 (96.8) |
| 112-day Shrinkage, µ-strain | -397 | -423 | -387 | -397 | -397 | -393 | | -505 | -480 | -507 |

Mixture Designation