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PROPERTIES OF HIGH-PERFORMANCE CONCRETE CONTAINING SHRINKAGE-REDUCING ADMIXTURE

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ABSTRACT

The effects of a recently developed shrinkage-reducing admixture on high-performance concrete properties are described. High-performance concrete mixtures containing silica fume were cast with and without shrinkage-reducing admixture. The mechanical properties, drying shrinkage, and resistance to restrained shrinkage cracking were investigated. The results show that the shrinkage-reducing admixture effectively reduced the shrinkage of high-performance concrete, and resulted in a significant decrease in restrained shrinkage cracking. © *1997 Elsevier Science Ltd*

Introduction

By definition, high-performance concrete should exhibit adequate workability, high strength, low permeability, superior dimensional stability, and long-term durability (1). Although the term "high-performance concrete" is often used to describe concrete in field applications, often times concrete does not possess all of the above properties. In particular, concrete mixtures with low water-binder ratios, incorporating highly-active pozzolans such as silica fume, have been observed to undergo significant shrinkage cracking, especially if adequate curing is not provided. This propensity for increased shrinkage cracking in these types of mixtures can be attributed in part to an increase in autogenous and dying shrinkage (2,3), as well as a reduction in creep (4,5).

To address the problems associated with drying shrinkage in field applications, several approaches have been proposed and followed. These approaches range from optimization of mixture proportions (by minimizing water content, selecting quality aggregates, etc.) to the utilization of shrinkage-compensating cement. In some cases, drying shrinkage can be controlled through proper mixture proportions and recommended concreting and curing practices. However, in cases where environmental conditions are quite severe (e.g., high temperature, low humidity, high wind velocity), or when locally available materials have a high propensity for shrinkage, it can be very difficult to prevent drying shrinkage cracking.

The use of shrinkage-compensating cement is a viable approach to attempt to minimize shrinkage cracking and has been used successfully in many applications. Nevertheless, this technology has not been fully embraced by the concrete construction market. This lack of acceptance is due in part to the difficulty in understanding and harnessing the benefits of shrinkage-compensating cement. For instance, due to the abundance of ettringite formed during the early hydration stages, rapid slump loss is often observed and can be problematic (6). In addition, since moisture is needed to trigger the expansive reaction, proper moist-curing is essential. Lastly, the amount of restraint provided within the concrete element (formwork, reinforcing steel, etc.) must be accurately designed and incorporated into the structure to achieve the desired restrained expansion. For these reasons, shrinkage-compensating cements have not been universally accepted.

A novel approach to minimizing drying shrinkage is the advent of shrinkage-reducing admixtures (SRAs). This family of admixtures confronts the shrinkage problem by reducing short- and long-term drying shrinkage, but without the reliance on expansive reactions. A detailed description of the shrinkage reducing mechanism of SRAs will be reported in other publications, but the following is a brief overview of the mode of action of SRAs.

Although the mechanisms of drying shrinkage of concrete are not fully understood, literature suggests that several mechanisms are dominant in different ranges of internal pore humidities (7). When considering concrete shrinkage in the 45-90% relative humidity range, capillary stress appears to be the predominant mechanism (8). When pore water evaporates from capillary pores in hardened concrete during drying, tension in the liquid is transferred to the capillary walls, resulting in shrinkage. For a given pore size distribution, the internal stress generated upon evaporation is proportional to the surface tension of the pore water solution. SRAs reduce drying shrinkage by lowering the surface tension of pore water (to approximately 40 dynes/cm) in hardened concrete. Thus, upon evaporation from capillary pores during drying, there is less tendency for shrinkage and resultant stresses.

The goals of the present study were to assess the effects of shrinkage-reducing admixtures on the properties of high-performance concrete, including fresh concrete properties, strength, and shrinkage characteristics. In addition, restrained shrinkage rings were used to assess the resistance to shrinkage cracking of high-performance concrete with and without SRA.

Experimental Program

The experimental program focused on the properties of high-performance concrete, with variables including the use of condensed silica fume and shrinkage reducing admixture. In all applicable cases, relevant ASTM standards were followed.

Materials, Mixture Proportions, and Experimental Procedures

Table 1 shows the chemical analysis for the ASTM Type I cement used in this investigation, and Table 2 provides the properties of the coarse and fine aggregates. The fine aggregate, which conformed to ASTM C 33, was a natural sand with a Fineness Modulus (FM) equal to 2.65. The coarse aggregate was a crushed quartz diorite, meeting specifications for ASTM C 33 (Size 67). Both aggregate types had been used successfully in a variety of high-performance concrete mixtures prior to the present study.

The shrinkage-reducing admixture was composed of a blend of propylene glycol derivatives. It was a 100% active liquid with a specific gravity of 0.95 and moderate water solubility. The condensed silica fume used in the study was in a slurry form, with a solids

TABLE 1
Chemical Analysis of ASTM Type I Cement

Chemical Analysis	%
SiO_2	21.11
Al_2O_3	4.59
Fe_2O_3	3.30
CaO	64.39
MgO	2.86
SO_3	2.32
Na_2O	0.09
K_2O	0.54
Alkalies as Na_2O	0.45
Loss on Ignition (950°C)	0.83
Compound Composition	%
C_3S	57
C_2S	17
C_3A	7
C_4AF	10

content of 50%. A naphthalene sulfonate formaldehyde type superplasticizer, which complied with ASTM C 494 Type A and F standards, was used in all mixtures.

Tables 3 and 4 show the mixture proportions and fresh concrete properties. A previously published high-performance concrete mixture proportioning method (1) was utilized in the present investigation, and a constant past volume fraction of 32.5% was selected. The four

TABLE 2
Properties of Coarse and Fine Aggregates

Property		Fine Aggregate (ASTM C33)	Coarse Aggregate (ASTM C33, Size 67)
Cumulative Percent Retained on Sieve Size:	19.0 mm		0
	12.5 mm		6
	9.5 mm	0	70
	4.75 mm	1	98
	2.36 mm	9	99
	1.18 mm	25	100
	600 μm	52	
	300 μm	82	
	150 μm	96	
	75 μm	100	
Bulk Specific Gravity		2.61	2.95
Fineness Modulus		2.65	6.73
Absorption Capacity (%)		1.1	0.5

TABLE 3
Concrete Mixture Proportions

Mixture Description	Cement (kg/m^3)	Silica Fume (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	HRWR (ml/100 kg of binder)	SRA (kg/m^3)	Water (kg/m^3)
Control Concrete	457	0	1092	779	1080	0	160
Concrete with 1.5% SRA	457	0	1092	779	1030	6.9	153.1
Silica Fume Concrete	423	34	1092	766	1175	0	160
Silica Fume Concrete with 1.5% SRA	423	34	1092	766	1110	6.9	153.1

*SRA dosage = 1.5% by weight of binder
*(water + SRA) ÷ (cement + silica fume) = 0.35 for all mixtures

concrete mixtures included a control, a mixture with 1.5% SRA (by mass of binder), a mixture containing 7.5% silica fume (solids by mass of cement), and a mixture containing both 1.5% SRA and 7.5% silica fume. For each mixture, the superplasticizer dosage was adjusted to achieve a target slump of 150-200 mm, a range which is desirable for many high-performance concrete applications. When superplasticizer or silica fume slurry were used, the amount of liquid present in these admixtures was subtracted from the mixing water. When SRA was added, a similar dosage of mixing water was removed to account for the water-reducing tendencies of SRA. This adjustment slightly decreased the water/binder ratio for concrete containing SRA to 0.34, compared to a water/binder ratio of 0.35 for mixtures without SRA.

As can be seen in Table 3, the addition of SRA had a minor water-reducing effect, and the amount of required superplasticizer to achieve the desired slump was slightly reduced for

TABLE 4
Fresh Concrete Properties

Mixture Description	Slump (mm)	Air Content (%)	Unit Weight (kg/m^3)	Initial Set (H:M)	Final Set (H:M)
Control Concrete	190	1.6	2526	5:48	8:27
Concrete with 1.5% SRA	190	1.6	2515	7:44	10:56
Silica Fume Concrete	180	1.7	2501	7:24	10:07
Silica Fume Concrete with 1.5% SRA	190	1.6	2496	10:07	12:14

these mixtures. It should be mentioned that another option could have been to maintain a constant superplasticizer dosage and reduce the mixing water to obtain the desired workability. This approach would have lowered the water/binder ratio of SRA mixtures. However, for the present study, a more controlled water/binder ratio was deemed to be more important from a research standpoint.

The air content and unit weight were not affected significantly by the use of SRA, but there was a noticeable retardation in initial and final set for concrete containing SRA. Set retardation can be offset by either modifying the mixture proportions (e.g., reduce superplasticizer or SRA dosage) or by using an accelerating admixture.

For each of the mixtures, cylindrical specimens (100 mm × 200 mm) were cast for the measurement of compressive strength (ASTM C 39) at 1, 7, 28 and 90 days, elastic modulus (ASTM C 469) at 28 days, and rapid chloride permeability (ASTM C 1202) at 28 and 90 days. For all of these tests, the specimens were moist-cured at 20°C and 100% RH until immediately before testing. Concrete prisms (75 mm × 75 mm × 285 mm), conforming to ASTM C 157, were cast to measure free shrinkage. After 24 hours, the prisms were demolded and stored thereafter at 20°C and 50% RH. Length change measurements were made on a daily basis for the first few weeks and periodically thereafter.

In addition to the shrinkage prisms, restrained rings were cast to measure shrinkage cracking. Theoretical and modeling aspects of this ring-type specimen can be found elsewhere in literature (9). For the present study, a concrete ring (50 mm in thickness, 150 mm in height) was cast around the outer perimeter of a steel pipe (ID = 250 mm, OD = 300 mm). The specimens were moist-cured for 24 hours, the top surface of the concrete rings were sealed with polyurethane, and the specimens were then placed under the same drying conditions as the previously described shrinkage prisms. The curing regimes were intentionally chosen to be identical for prisms and rings to allow for correlation between measured shrinkage strains and cracking. A curing period of 24 hours was selected to simulate minimal field-curing conditions, and also to accelerate the onset of cracking. Shrinkage rings were regularly monitored for cracking through the use of a magnifying microscope.

Experimental Results and Discussion

The results of compressive strength, elastic modulus, and rapid chloride permeability testing are furnished in Table 5. The addition of SRA tended to reduce compressive strength, especially when tested at an age of 1 day. This strength loss is mainly attributed to the effects of SRA on early cement hydration. However, at later ages, the compressive strength of concrete containing SRA was only 8–9% less than companion mixtures without SRA. As previously stated, the superplasticizer dosage was lowered for SRA mixtures to account for water-reducing effects of SRA and to minimize changes in water/binder ratio. However, if the superplasticizer dosage was kept constant and the amount of mixing water was decreased to attain the desired slump, the difference in compressive strengths would not have been as evident. There was no significant effect of SRA addition on the rapid chloride permeability of concrete.

The free shrinkage of prisms after 120 days of drying is shown in Figure 1. The use of SRA significantly reduced the drying shrinkage of high-performance concrete (both with and without silica fume). This shrinkage reduction was more pronounced when SRA was used in conjunction with silica fume, as reflected in the 52% reduction in drying shrinkage at 28 days

TABLE 5
Hardened Concrete Properties

Mixture Description	Compressive Strength (MPa)				Elastic Modulus (GPa)	Rapid Chloride Permeability* (Coulombs)	
	1-day	7-days	28-days	90-days	28-days	28-days	90-days
Control Concrete	31.2	51.9	63.9	74.1	39.5	2330	1900
Concrete with 1.5% SRA	25.0	48.2	58.7	67.6	36.8	2250	1990
Silica Fume Concrete	30.6	56.0	76.4	83.6	40.7	520	260
Silica Fume Concrete with 1.5% SRA	25.5	50.7	71.7	76.9	37.4	430	260

*ASTMC 1202

and 43% reduction in drying shrinkage at 120 days, compared to silica fume concrete without SRA. For comparison, the addition of SRA to the control concrete yielded a shrinkage reduction of 35% at 28 days and 29% at 120 days. Although the specific mechanisms behind the improved efficacy of SRA in silica fume concrete are not fully understood, there appears

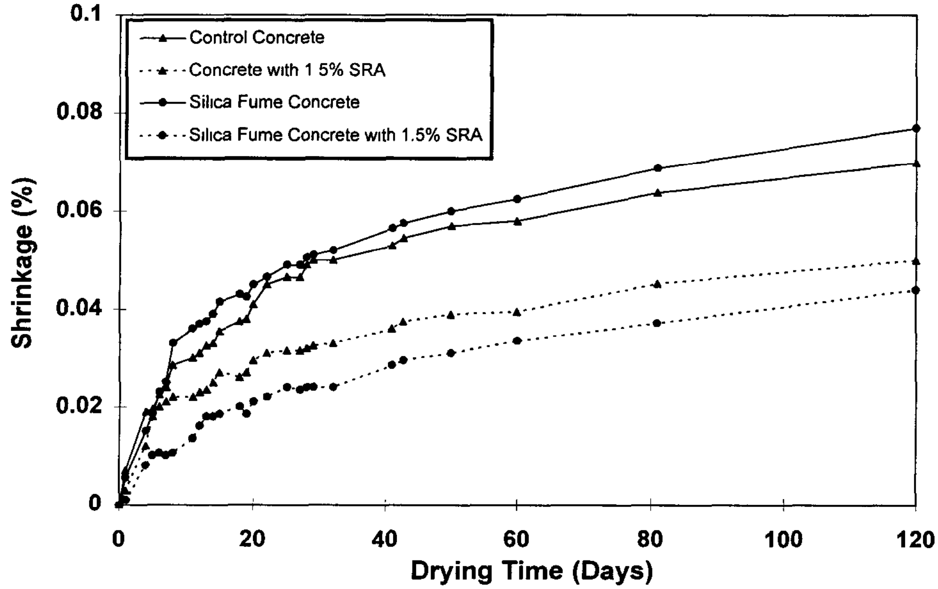

FIG. 1.
Drying shrinkage of High-Performance Concrete with and without SRA (ASTM C 157, 1-day moist-cure).

TABLE 6
Summary of Free Shrinkage Measurements and Restrained Shrinkage Ring Cracking

Mixture Description	28-day Drying Shrinkage (%)	120-day Drying Shrinkage (%)	Average Time to Ring Cracking (days)	Average Crack Area per Ring (mm^2)
Control Concrete	0.049	0.070	44	5.9
Concrete with 1.5% SRA	0.032	0.050	No cracks after 120 days	0
Silica Fume Concrete	0.051	0.077	38	25.3
Silica Fume Concrete with 1.5% SRA	0.024	0.044	95	3.1

to be a synergistic relationship between the use of silica fume and SRA. This behavior has been observed in other mortar and concrete mixtures containing both silica fume and SRA.

It should be noted that the shrinkage results given in Figure 1 represent concrete with only 24 hours of moist curing. The efficiency of SRA in reducing shrinkage was found to be quite favorable under these conditions, but the ability of SRAs to reduce shrinkage is further improved as the amount of curing is increased. Thus, the present study illustrates that SRAs provide an effective method of reducing shrinkage of poorly-cured concrete. However, additional moist-curing is recommended for field applications to not only improve the quality and intrinsic shrinkage resistance of concrete, but also to extract the maximum benefit from shrinkage-reducing admixtures.

A summary of restrained shrinkage cracking results is shown in Table 6. The results shown are the average of two restrained shrinkage rings for each concrete mixture. The average time to first crack for the control mixture was 44 days, whereas a similar mix containing 1.5% SRA had not yet cracked after 120 days of drying. The silica fume concrete mixture (without SRA) suffered cracking at an average time of 38 days, whereas companion rings containing 1.5% SRA cracked at an average time of 95 days. At the end of the 120 day exposure period, the silica fume concrete containing SRA exhibited a 88% reduction in cracking, compared to silica fume rings without SRA.

Conclusions

This paper has summarized the results of a study on the effects of a recently developed shrinkage-reduced admixture on high-performance concrete. Based on these findings, the following conclusions can be drawn:

1. The use of SRA in high-performance concrete was found to significantly reduce drying shrinkage and restrained shrinkage cracking in laboratory ring specimens.
2. The effectiveness of SRA in reducing shrinkage was observed despite a very short (24-hours) moist-curing period. However, proper curing should remain an essential component in concrete field applications, and this improved curing would also increase the efficacy of SRAs in reducing shrinkage and subsequent cracking.
3. Concrete containing SRA exhibited lower early strengths than companion mixtures

without SRA. This strength loss can be offset to some degree by reducing the mixing water to account for the water-reducing tendency of SRA addition.

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