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Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

CONCRETE SOCIETY
OF SOUTHERN AFRICA

admin@concretesociety.co.za
www.concretesociety.co.za

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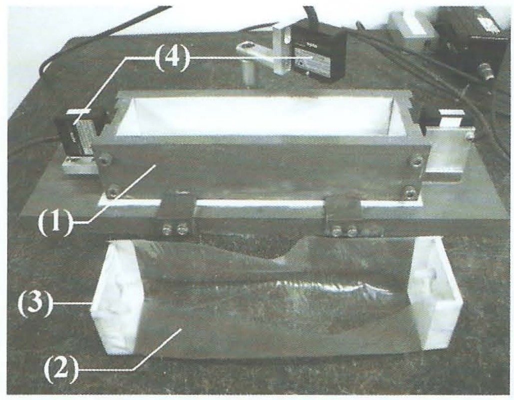
***Keywords**: concrete; plastic shrinkage; self-consolidating concrete; shrinkage cracking.*

INTRODUCTION

Self-consolidating concrete (SCC) is a fluid concrete cast without vibration. This construction material is increasingly being employed in flat structures, such as slabs or industrial floors, due to its self-leveling ability. This type of construction, however, is vulnerable to plastic shrinkage cracking, especially when concrete is exposed to hot and/or windy conditions.[1] Plastic shrinkage is the contraction that occurs in fresh concrete before and during setting. Plastic shrinkage is often explained by the presence of water menisci on the concrete surface, when the evaporation rate is greater than the bleeding rate.[2] Water menisci generate a negative capillary pressure that tends to pull the solid particles together and consequently causes shrinkage. Capillary pressure can also be created by self-desiccation, inside concrete, due to cement hydration.[3] In most structures, plastic shrinkage is restrained. As a result, tensile stresses develop and concrete may crack if stresses exceed cracking capacity. The risk of plastic shrinkage cracking is high for concrete with high binder content (cement and filler content) and low waterbinder ratio (*w/b*). In this paper, ordinary concrete (OC) means vibrated concrete designed with the same materials and having the same compressive strength as the associated SCC mixture. A literature review reveals that SCC mixtures usually contain higher binder content than ordinary concrete mixtures.[4,5] Normally, binder content of SCC ranges from 450 to 650 kg/m^3, while binder content of OC ranges from 280 to 400 kg/m^3. In the same way, the *w/b* of SCC is usually lower than the *w/b* of OC. As a result, some SCC is suspected to be more sensitive to early-age cracking.[6] Recent studies seem to confirm this claim.[7,8] Indeed, some SCC mixtures were found to have greater plastic shrinkage than some OC mixtures.



1: 70x70x280 mm mold; 2: plastic sheet
3: reflecting plate; 4: laser sensors

Fig. 1 - Plastic shrinkage measurement device

RESEARCH SIGNIFICANCE

SCC is often used in horizontal applications, structures that are vulnerable to plastic shrinkage cracking. SCC is a priori more susceptible to crack at the fresh state than OC because of higher binder content and lower *w/b*. This study aims at verifying this hypothesis. Five SCC mixtures were investigated and compared to OC mixtures designed with the same constituents and with the same compressive strength. Plastic shrinkage of each composition was measured in various environmental conditions. Cracking was also studied with a restrained shrinkage test.

EXPERIMENTAL PROGRAM

The test procedures and materials used in the study are described in the following.

Free plastic shrinkage test

As shown in Fig. 1, the specimen setup for plastic shrinkage measurement consists of two elements: 1) a steel mold of inner size 70 x 70 x 280 mm, whose internal sides are covered by Teflon; and 2) an envelope formed by two PVC plates, called reflecting plates, attached to a plastic sheet. Concrete is cast in this envelope positioned in the mold. Talc is powdered between the plastic sheet and the mold to limit friction between concrete specimen and mold. When the specimen shrinks, for example because of drying, the reflecting plates are dragged along by the concrete. Two laser sensors are used to measure the plates' displacement, from which the horizontal deformation is calculated, that is, plastic shrinkage (Fig. 2). A third laser sensor above the specimen is used to measure the displacement of a thin Teflon 10 x 10 mm square plate, which is placed on the concrete surface. Because Teflon is denser than water but less dense than concrete, the thin plate stays on the concrete top layer in spite of any bleeding. From this measurement, the vertical deformation, that is, settlement, is deduced. The relative precision of measured deformations is ±5%. During testing, evaporation is measured in terms of weight loss of a cylindrical sample 70 mm high with a 100 mm diameter. The main driving force of plastic shrinkage is a negative pore water pressure, called capillary pressure, generated by menisci at the surface of concrete (due to desiccation) or inside (due to self-desiccation). Thus, the knowledge of capillary pressure development is important for the comprehension of shrinkage phenomena.[2,9] For this reason, the test setup described in Fig. 3 was developed. Two porous ceramic cups were placed horizontally in a mold 70 mm high with a 100 mm diameter, located at 10 and 35 mm below the concrete top surface. The ceramic cups were connected to pressure sensors through thin water pipes.

Tests started 20 minutes after adding water in the mixing process. All data (plastic shrinkage, settlement, temperature, weight, and capillary pressure) was logged on a computer at 5-minute intervals for a period of 24 hours.

Restrained plastic shrinkage test

The restrained plastic shrinkage test used was derived from the procedure followed by Soroushian and Ravanbakhsh[10] The device consists of a 70 x 200 x 400 mm mold with three stress risers used to provide restraint and promote cracking (Fig. 4). Cracking is created above the central riser through the depth and across the width of the slab. It is worth noting that the plastic shrinkage test depends on the specimen geometry and the drying surface. Several tests on this device showed that only concrete having a deformation larger than 2200 µm/m can crack. During testing, the time at which the concrete surface starts cracking is recorded. Six hours after concrete placement, maximum crack width is measured with a hand-held microscope (accuracy ±50 µm).

Environmental conditions of tests

Tests are performed in an air-conditioned room with a temperature of 20 ± 1 °C and a relative humidity of 50 ± 5%.

Free plastic shrinkage tests can be performed in the following environmental conditions:

1) Sealed condition—The top surface of the specimen is covered by a plastic sheet to prevent drying. Measured shrinkage is an autogenous shrinkage, that is, only caused by cement hydration.
2) No-wind condition—The top surface is allowed to dry in the room. Shrinkage is caused by both drying and hydration.
3) Wind condition—A fan producing a wind speed of 5 m/s is placed 40 mm from the specimen to accelerate evaporation rate.

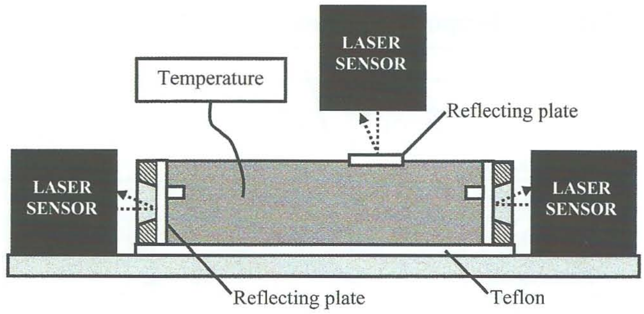


Fig. 2 - Schematic section view of plastic shrinkage measurement

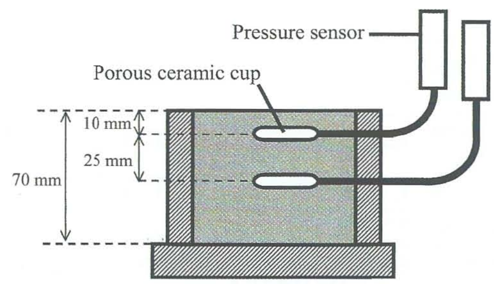


Fig. 3 - Schematic section view of capillary pressure measurement

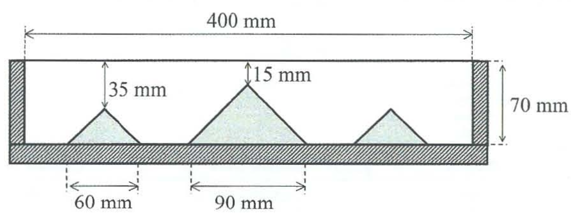


Fig. 4 - Schematic section view of restrained shrinkage device

Restrained plastic shrinkage tests are done in the wind condition. In fact, this kind of passive device can produce cracking only in severe drying conditions, that is to say, when wind is applied.

Materials and concrete mixtures

Five SCC mixtures were investigated. Table 1 summarizes the mixture proportions, the fresh concrete properties, and the compressive strength for the various mixtures. Produced in concrete plants in France, these mixtures are made of different constituents (cement types, nature of aggregates) and have various 28-day compressive strengths (ranging from 25 to 50 MPa). An OC composition was derived from each SCC composition (Table 1), that is, designed with the same constituents. The specifications for OC were the following: approximately the same 28-day strength as the associated SCC composition, and a slump between 100 and 150 mm. The materials of each SCC and OC pair are described in Table 2. It should be noted that all of SCC mixtures were made with limestone filler.

RESULTS AND DISCUSSION

Origin of plastic shrinkage

Plastic shrinkage can be caused by both water evaporation

Table 1—Proportions and properties of studied mixtures

	SCC and OC pair name									
	C1		C2		C3		C4		C5	
	SCC1	OC1	SCC2	OC2	SCC3	OC3	SCC4	OC4	SCC5	OC5
Gravels, kg/m^3	792	1060	825	1100	742	1030	790	1070	906	990
Sand, kg/m^3	811	720	950	845	857	760	860	780	768	810
Cement, kg/m^3	315	350	330	282	350	350	350	360	292	300
Filler, kg/m^3	160	0	110	30	130	0	150	0	204	50
HRWRA, kg/m^3	3.75	0.35	4	1.18	6	1.7	5.4	1	5.4	1.5
VEA, kg/m^3	0.5	0	0	0	0.5	0	3.4	0	0.5	0
Water, kg/m^3	190	180	180	170	195	175	187	170	160	170
w/c	0.61	0.51	0.55	0.60	0.57	0.50	0.53	0.47	0.54	0.57
w/b	0.41	0.51	0.41	0.54	0.41	0.50	0.37	0.47	0.32	0.49
V_{paste}, L/m^3	352	291	326	271	357	286	354	284	332	285
Slump, mm	—	150	—	140	—	150	—	100	—	110
Slump flow, mm	680	—	680	—	700	—	680	—	760	—
Laitance, %	5	—	8	—	6	—	15	—	5	—
f_{c28d}, MPa	30	30	40	37	42	41	48	53	47	45

Notes: HRWRA = high-range water-reducing admixture; VEA = viscosity-enhancing agent; b = binder (cement + filler); V_{paste} = volume of paste. Percentage of laitance is result of screen stability test proposed by AFGC.[11] Segregation resistance decreases when percentage of laitance increases. Below 15% of laitance, segregation resistance is considered good.

Table 2—Constituents of concrete mixtures

	SCC and OC pair name				
	C1	C2	C3	C4	C5
Gravel	6.3/20 mm rolled gravel	6/10 mm crushed gravel	6.3/20 mm rolled gravel	4/12.5 mm rolled gravel	3/8 mm rolled gravel
Sand	0/4 mm river sand	0/4 mm sea sand	0/4 mm river sand	0/3 mm sea sand	0/4 mm river sand
Cement	CEM2 32.5	CEM2 42.5	CEM1 52.5	CEM1 52.5	CEM1 52.5
Filler	Limestone	Limestone	Limestone	Limestone	Limestone
HRWRA	Polycarboxylate	Polycarboxylate	Polycarboxylate	Polycarboxylate	Polycarboxylate
VEA	Organic polymer	—	Organic polymer	Nano silica	Organic polymer

Notes: HRWRA = high-range water-reducing admixture; and VEA = viscosity-enhancing agent.

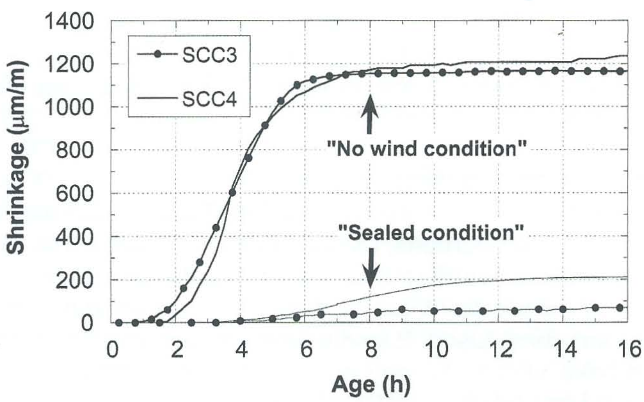


Fig. 5 - Plastic shrinkage versus time for Mixtures SCC3 and SCC4

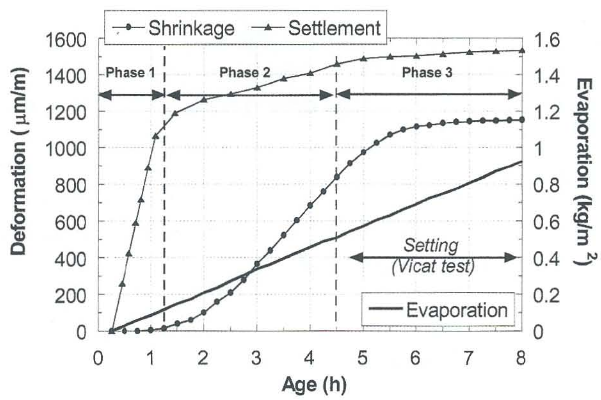


Fig. 6 - Development of plastic shrinkage, settlement, and evaporation for no-wind condition (Mixture SCC3)

and cement hydration. In the case of low water-cement ratio (*w/c*) concrete, such as high-performance concrete (HPC), the autogenous part of shrinkage is important. In the case of SCC, one can assume that plastic shrinkage is mainly a drying contraction when the *w/c* is high (more than 0.5). To verify this hypothesis, two SCC mixtures (SCC3 and SCC4) were tested in the sealed condition (Fig. 5). At the age of 16 hours, autogenous shrinkage represents less than 15% of total shrinkage in the case of Mixture SCC4 and less than 5% of the total shrinkage of Mixture SCC3. As a result, one could conclude that evaporation is the main cause of plastic shrinkage of our mixtures.

Interpretation of plastic shrinkage curves

Before comparing SCC and OC behaviors, one should first understand basic shrinkage phenomena. The interpretation

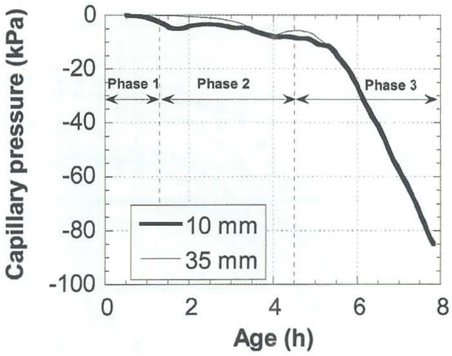


Fig. 7 - Capillary pressure at 10 and 35mm depth for nowind condition (Mixture SCC3)

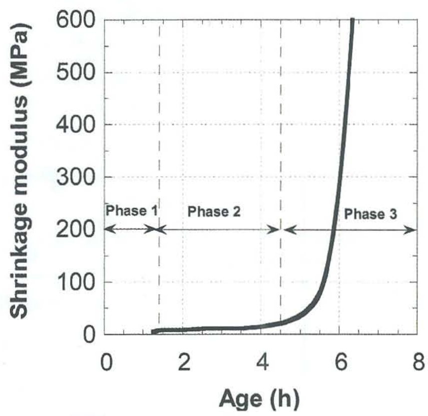


Fig. 8 - Shrinkage modulus for no-wind condition (Mixture SCC3)

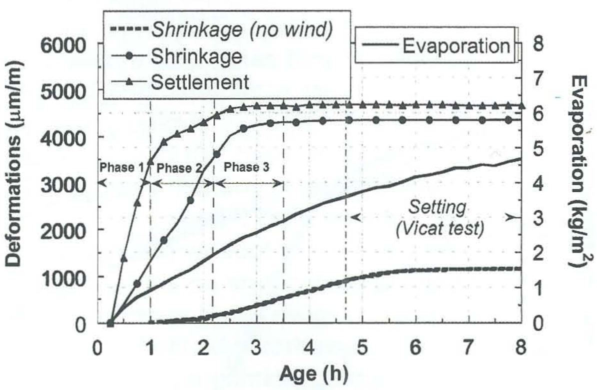


Fig. 9 - Plastic shrinkage, settlement, and evaporation for wind condition and plastic shrinkage for no-wind condition (Mixture SCC3)

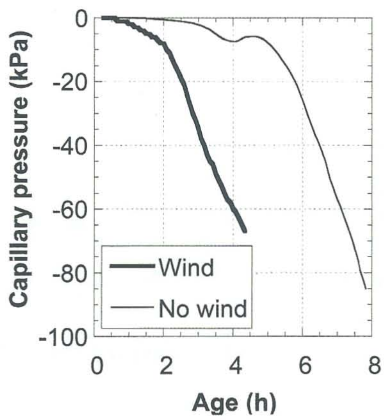


Fig. 10—Capillary pressure evolution in both no-wind and wind conditions (Mixture SCC3).

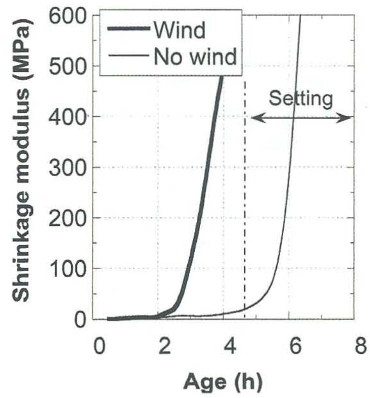


Fig. 11—Shrinkage modulus for both no-wind and wind conditions (Mixture SCC3)

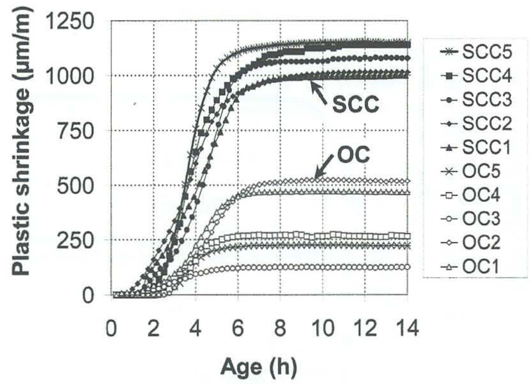


Fig. 12—Plastic shrinkage of SCC and OC mixtures in no-wind condition.

of curves derived from shrinkage measurements is also important. Figure 6 presents typical shrinkage, settlement, and evaporation curves for Mixture SCC3 for the no-wind condition. It can be observed that evaporation rate is almost constant during shrinkage development (approximately 0.1 kg/m^2/h). Therefore, any change in deformation rate is only caused by changes in concrete microstructure. Three phases can be distinguished. This agrees with results in the literature.[12-15]

Phase 1—A high settlement rate is recorded. This deformation results from a chemical shrinkage because the absolute volume of hydration products is less than the total volume of the reactants. Settlement is also the effect of gravity. This consolidation leads to an increase of packing density of concrete, which forces water to percolate to the top surface. As a result, bleeding may occur during this phase, and settlement rate data can be used to assess bleeding rate. When settlement rate decreases (at the age of 1 hour), the sample begins to support its own weight. During this phase, no shrinkage can be observed.

Phase 2—Volumetric contraction is transmitted horizontally little by little. The beginning of shrinkage first indicates that

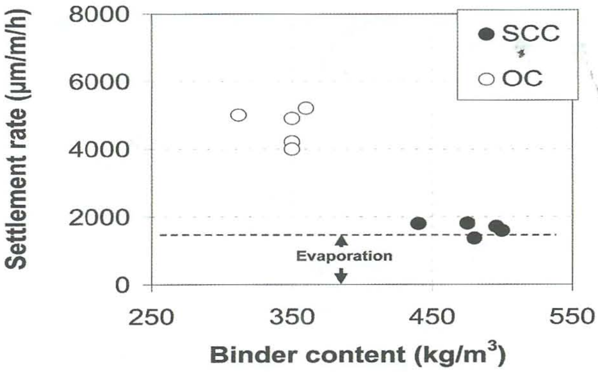


Fig. 13—Initial settlement rate versus powder content of SCC and OC mixtures for no-wind condition.

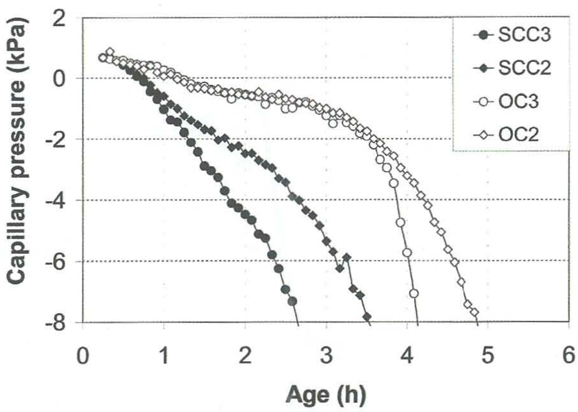


Fig. 14—Capillary pressure of SCC and OC mixtures in no-wind condition.

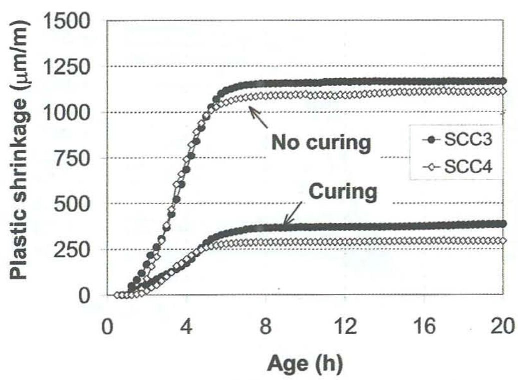


Fig. 15—Plastic shrinkage with and without curing in no-wind condition (Mixtures SCC3 and SCC4)

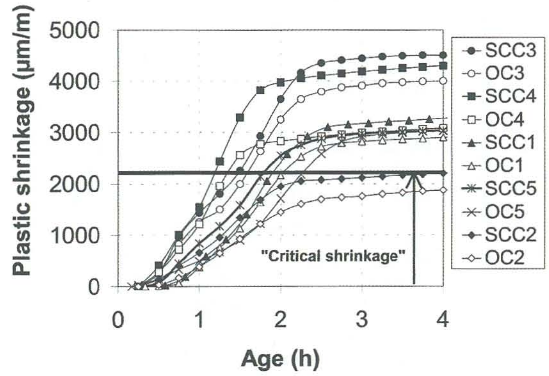


Fig. 16—Plastic shrinkage of SCC and OC mixtures in wind conditions ("critical shrinkage" indicates approximate shrinkage value beyond which specimen cracks)

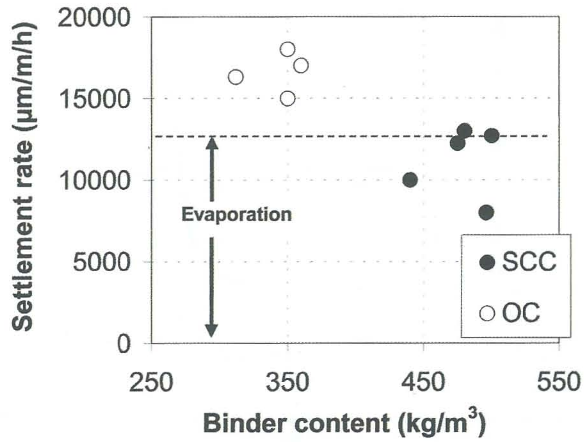


Fig. 17—Initial settlement rate versus powder content of SCC and OC mixtures of wind condition.

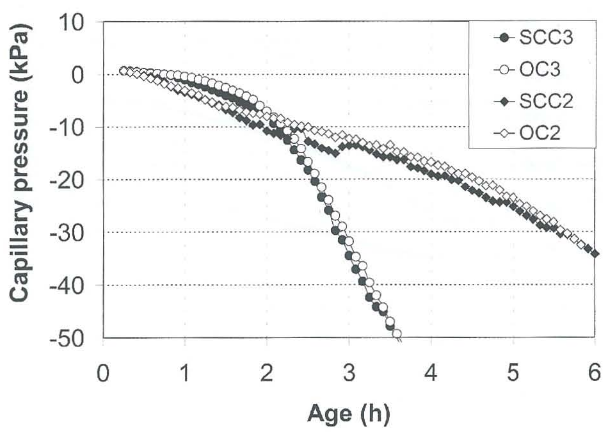


Fig. 18—Capillary pressure of SCC and OC mixtures in wind condition.

pore water pressure is decreasing, as revealed in Fig. 7, due to a complex menisci system on the drying surface. As shown by Radocea,[16] capillary forces are not large enough to create horizontal deformation. Shrinkage also means that the concrete internal friction angle is adequately high. In other words, concrete particles must interact. Granular interactions are gradually favoured by consolidation, an increase of solids volume (hydration), and a decrease of water content (consolidation, hydration, and evaporation). During Phase 2, shrinkage rate increases until it remains almost constant.

Phase 3—Because of setting, volumetric contraction is increasingly hindered and, consequently, the shrinkage curve flattens. Initial and final setting times were measured by the Vicat needle apparatus in accordance with European Standard EN-196-3 on a mortar mixture proportioned using the concrete-equivalent-mortar (CEM) method.[17] Vicat test results confirm that the third phase fits well with setting (initial setting equals approximately 4.7 hours and final

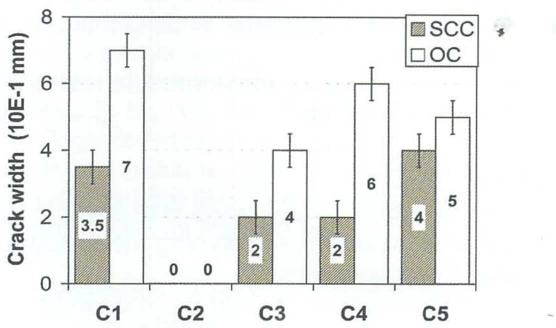


Fig. 19—Maximum crack width of all SCC and OC pairs.

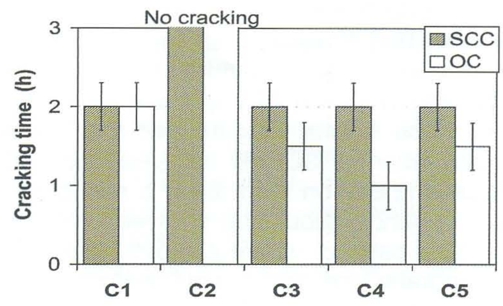


Fig. 20—Cracking time for all SCC and OC pairs.

setting equals approximately 8 hours). Radocea[9] defined shrinkage modulus as the ratio of an increment of capillary pressure and the corresponding increment of plastic shrinkage. Shrinkage modulus increases rapidly during this stage (Fig. 8). This is caused by an increase of skeleton stiffness owing to setting.

Figure 9 presents typical plastic shrinkage, settlement, and evaporation curves for the SCC3 mixture under the wind condition. The evaporation rate is initially 0.9 $kg/m^2/h$. Consequently, shrinkage amplitude at 8 hours is approximately four times higher than it is in the no-wind case. Moreover, the deformation kinetics is changed when wind is applied; the previously described phases appear but are shifted in time.

Phase 1 and 2—Like evaporation rate, initial settlement rate is multiplied approximately by nine. Settlement is mainly a consequence of drying. Thus, one could expect that bleeding water evaporates instantly at the concrete surface. This is confirmed by capillary pressure measurement because water pressure decreases almost immediately at the start of the test (Fig. 10). As a result, horizontal deformation appears very quickly.

Phase 3—Like in the case of the no-wind condition, the shrinkage curve flattens. Nevertheless, this occurs long before setting. Figure 11 shows the change of shrinkage modulus with and without wind. The evolution of shrinkage modulus depends on environmental conditions. Therefore, shrinkage modulus is not necessarily linked to setting.

Before setting, concrete can be considered a granular media, like a soil. The drying shrinkage curve of a soil is known to typically present two stages.[18,19] During Phase 1, volumetric contraction is proportional to water loss (like in Phase 2 described previously). During Phase 2, contraction is less than water loss that results in a flattening of the shrinkage curve (as observed in Phase 3). Phase 2 corresponds to a shrinkage limit; the granular media has been packed during Phase 1 so that it is then dense enough to resist the capillary pressure. Based on results in the literature, Phase 3 of shrinkage curve can be explained, in the wind condition, by an increase of packing density of concrete.

Finally, the important thing to note from this analysis is that, depending on evaporation rate, plastic shrinkage may stop before or during setting.

	SCC1	OC1	SCC2	OC2	SCC3	OC3	SCC4	OC4	SCC5	OC5
Time, hours	8.5	7.5	9.5	8	7.5	5	8	6	7	5.5

Table 3—Time to reach maximum shrinkage

Comparison of SCC and OC in no-wind condition

Figure 12 presents a noteworthy result: in the no-wind condition, plastic shrinkage of SCC mixtures is at least twice as high as plastic shrinkage of OC mixtures. Measurements confirm the a priori concerning SCC mixture design and plastic shrinkage. The other experimental results reveal some elements to explain the difference between SCC and OC.

- Bleeding rate can be evaluated by settlement rate[20] (that is, initial slope of the settlement curve). As bleeding is known to be dependent on fine elements content,[20,21] settlement rate was plotted versus binder content in Fig. 13. It appears that settlement rate of SCC is lower than settlement rate of OC. Moreover, settlement rate of SCC is approximately equal to evaporation rate (evaporation rate of 0.1 $kg/m^2/h$ is equivalent to a deformation rate of 1570 μm/m/h, if drying is totally transformed in a vertical deformation). Hence, bleeding of SCC must be almost zero, contrary to OC, and the high binder content of SCC undoubtedly gives an explanation for its lack of bleeding. The lower settlement rate could be also correlated to the presence of viscosityenhancing agent (VEA) in some SCC mixtures. Indeed, VEA increases the pore water viscosity[22] and, as result, should decrease solid particles sedimentation.[20]
- Capillary pressure decreases faster in the case of SCC (Fig. 14). This results first from the lack of bleeding. This could be also the effect of a lower w/b of SCC because capillary pressure is inversely proportional to pore diameter, according to the Laplace equation.
- In the no-wind condition, Phase 3 is related to setting. Due to higher high-range water-reducing admixture dosage, setting of SCC is delayed compared to setting of OC. As a result, the period allowed for shrinkage development may be longer for SCC. Table 3 reveals that shrinkage final amplitude is actually reached later in the case of SCC. All of the tested SCC mixtures exhibit higher plastic shrinkage than the OC mixtures. Thus, SCC mixtures are likely more vulnerable to plastic shrinkage cracking. This could not be verified with the restrained shrinkage test used in this study. As previously noted, this device cannot produce cracking when the critical

shrinkage amplitude, approximately 2200 μm/m, is not reached during Phase 3, defined in Fig. 6. It must be emphasized that these results are based on a limited set of mixtures. They provide only trends regarding SCC behavior. Nevertheless, from a practical point of view, these results indicate that it is preferable to limit evaporation of SCC at the fresh state. One way to reduce evaporation is to apply a curing compound. Such compounds should be sprayed on the concrete surface after casting, where it rapidly produces a very thick membrane, preventing moisture loss. In this study, a curing compound made of copolymer diluted in solvent was tested. Figure 15 shows a comparison of the plastic shrinkage between the SCC3 and the SCC4 mixtures in the no-wind condition with and without curing. The curing agent was found to be efficient because the final amplitude of shrinkage was reduced by three times. Finally, cured SCC mixtures have plastic shrinkage of the same order of magnitude as OC mixtures.

Comparison of SCC and OC in wind condition

When drying conditions become severe, the difference between the amplitude of plastic shrinkage of the SCC and the OC mixtures, made of the same constituents, decreases considerably (Fig. 16). The previous points can be discussed again.

- Settlement rates of SCC and OC mixtures are slightly different when wind is applied (Fig. 17). Evaporation rate exceeds bleeding rate for all mixtures and, therefore, OC mixtures are not protected any more against drying by a layer of bleed water.
- As shown in Fig. 18, capillary pressure evolution is identical for an SCC mixture and the associated OC mixture.
- In the wind condition, all plastic shrinkage occurs before setting. The difference in setting time between SCC and OC mixtures does not produce a difference in shrinkage.

Figure 19 and 20 show the results of the restrained shrinkage tests performed in the wind condition. The amount of cracking was found to be lower for the SCC mixtures; the crack width of SCC mixtures is smaller than the crack width of the OC mixtures (Fig. 19). Moreover, SCC mixtures tend to crack later (Fig. 20). It is worth noting that Mixtures SCC2 and OC2 did not crack because the maximal shrinkage value was lower than 2200 μm/m. This result seems to be coherent with the shrinkage and capillary pressure measurements as Mixtures SCC2 and OC2 have the lowest shrinkage and the slowest capillary pressure development. The difference in constituents, particularly the cement type, could provide an explanation for the difference in behavior between C2 mixtures and the other mixtures. For instance, it is likely that the pores are larger in the C2 mixtures.

In spite of little variation in plastic shrinkage in the wind condition, the tested OC and SCC mixtures do not exhibit the same behavior, in most cases, regarding cracking. Therefore, it appears that plastic shrinkage measurements do not necessarily accurately predict concrete cracking potential at the fresh state. Hammer12,23 proposed to study plastic cracking phenomenon with a load and capacity concept, where the load is plastic shrinkage and the capacity is the strain capacity of concrete. It is believed that the highly fluid consistency of SCC mixtures results in high strain capacity.

SCC mixtures more easily accommodate restrained plastic shrinkage by plastic flow.[24]

CONCLUSIONS

Based on the experimental results presented in this paper, the following conclusions concerning the tested SCC and OC mixtures can be made:

1. When the evaporation rate is moderate (drying at 20 °C and a relative humidity of 50%), plastic shrinkage occurs before and during setting. In this environmental condition, drying shrinkage is higher in the case of SCC than for OC.
   As revealed by settlement measurements, the difference in shrinkage between the two types of concrete is mainly due to the difference in bleeding. While bleedwater offers to OC a natural protection (curing) against evaporation, bleeding of SCC is very low because of its high binder content and the presence of VEA. Consequently, capillary pressure in SCC can develop at a faster rate. The difference in shrinkage may also come from the lower w/b of SCC, which may generate rapid capillary pressure, and from the higher high-range water-reducing admixture content of SCC, which may delay setting; and
2. When the evaporation rate is high (windy condition), plastic shrinkage occurs only in the plastic state, that is, before setting. In this case, SCC and OC mixtures made of the same constituents exhibit almost the same plastic shrinkage.
   In fact, all differences in shrinkage due to mixture design effects (bleeding, setting) vanish when the evaporation rate becomes high. Restrained shrinkage tests performed in the windy condition revealed that SCC tends to have less cracking than OC. Because of its fluid consistency, SCC is thought to have a greater strain capacity than OC in the fresh state.

This study gives certain trends in SCC behavior at the fresh state. Because limited sets of concrete mixtures were tested, these results should be confirmed on other SCC and OC mixtures. Following this research, a study is in progress to evaluate the influence of paste volume, addition type, and addition/cement ratio on plastic shrinkage cracking. From the practitioner's point of view, curing of SCC used in horizontal applications should be recommended to compensate for the lack of bleeding and then to reduce the potential of cracking. In the future, a study on plastic shrinkage cracking of SCC should be carried out in different ways. Restrained shrinkage tests could be undertaken with a more sophisticated apparatus[23,25] (active restrained shrinkage test) to compare strain capacity of SCC and OC in various environmental conditions. Modeling could also be a way to better understand early-age shrinkage cracking.

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