Cement and Concrete Research 39 (2009) 141–146

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Influence of shrinkage-reducing admixtures on the reduction of plastic shrinkage cracking in concrete

José Mora-Ruacho [a,*], Ravindra Gettu [b], Antonio Aguado [c]

[a] Faculty of Engineering, Civil Engineering Department, Autonomous University of Chihuahua, P.O. Box 1528 C, 31160, Chihuahua, Chihuahua, Mexico
[b] Indian Institute of Technology Madras, Department of Civil Engineering, Chennai 600036, India
[c] Universitat Politècnica de Catalunya, Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports, Jordi Girona 1-3, Mod. C1, 08034, Barcelona, Spain

ARTICLE INFO

Article history:
Received 15 June 2007
Accepted 29 November 2008

Keywords:
A. Drying
A. Fresh concrete
C. Durability
C. Shrinkage
D. Admixtures

ABSTRACT

Fresh concrete exposed to high evaporation rates is prone to plastic shrinkage cracking, especially in structures with large surface area/volume ratios. The present work shows that the reduction of the surface tension of the mixing water is an effective way for decreasing such cracking. In this study, conventional and high strength concretes with superplasticizers and shrinkage reducing admixtures (SRAs) were exposed to drying in the plastic state. Continuous monitoring of the surface displacement facilitated the identification of the different stages of plastic shrinkage cracking. Measurements of capillary pressure, settlement, internal temperature and evaporation rate were also made. The results show the effectiveness of SRAs in reducing plastic shrinkage cracking, even in high strength concrete. This is attributed to the reduction in the evaporation rate, delay of the peak capillary pressure due to the development of menisci in the pores and lower settlement.

1. Introduction

Plastic shrinkage in concrete is a complex interaction of internal and external phenomena, and is governed mainly by the loss of water due to drying, which leads to the formation of water menisci that exert contraction forces within the microstructure. Plastic shrinkage can result in cracking, especially under hot, dry and windy weather conditions [1–4]; structures or elements having higher surface to volume ratios are prone to such cracking. Recently, Lura et al. [5] have given a clear explanation of the mechanisms governing plastic shrinkage cracking in concrete. According to them, the driving forces for such cracking are high evaporation rates that lead to the menisci and high tensile stresses, differential settlement, temperature gradients and autogenous shrinkage. Consequent plastic shrinkage cracks occur without any definite pattern with lengths ranging from few centimeters to several metres, and widths that can attain values of 0.1 to 3 mm [1].

Plastic shrinkage cracking has often been tackled by the incorporation of fibres in concrete [3,6,7], which arrest crack opening and, consequently, limit the crack width. The reduction of the surface tension of water used in the concrete is an interesting alternative; an effective way of doing this is through the incorporation [8,9] of a polypropylene glycol based shrinkage reducing admixture (SRA). Extensive studies of the effect of such SRAs on concrete behaviour, over the past two decades, have shown that, in hardened concrete, the SRA leads to lower drying and autogenous shrinkage strains, lower drying creep, modifies the morphology of the hydrated cement paste and its growth rate, and reduces the evaporation rates and sorptivity, though the strength and modulus of elasticity can also decrease [8,10–17]. There are, however, few studies on the plastic shrinkage cracking of concretes with SRAs. Preliminary work by Mora et al. [18,19] showed that the SRA is as effective in decreasing crack widths as polymeric fibres. Recently, Lura et al. [5] showed that mortars with SRA exhibit fewer and narrower cracks than plain mortars exposed to the same drying conditions.

The present work aims at evaluating the behaviour of conventional and high strength concretes incorporating commercially available SRAs and superplasticizers through measurements of crack width, capillary pressure, settlement, internal temperature and evaporation rate during plastic shrinkage. One interesting aspect of the crack width measurement is that the deformation and subsequent crack opening due to shrinkage are monitored continuously, which permit the identification of the different stages involved in the cracking process.

2. Research significance

Shrinkage crack reduction is important from the point of view of durability, as well as that of strength, particularly in structures such as slabs, bridge deck overlays, tunnel linings and pavements. Recent research work has shown that the use of glycol based SRAs can lead to reduction in plastic shrinkage cracking, in addition to the more

* Corresponding author. Tel.: +52 614 442 9502; fax: +52 614 442 9500.
E-mail address: jmora@uach.mx (J. Mora-Ruacho).

0008-8846/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2008.11.011

Table 1
Details of the chemical admixtures used

Designation	Nature	Density (g/cm^3)	% Active material
Superplasticizers			
D	Melamine based, non-surfactant	1.15	44.4
G	Polycarboxylate based, non-ionic surfactant	1.06	21.6
Shrinkage reducing admixtures			
E	Polypropylene glycol based, non-ionic surfactant	0.90	96.0
S	Polypropylene glycol based, non-ionic surfactant	0.95	76.0
R	Wax-based, non-ionic surfactant	0.94	39.8

recognised benefit of lower drying shrinkage. The incorporation of the SRA offers an alternative to the control of plastic shrinkage cracking through the addition of fibres to the concrete. Therefore, studies of plastic shrinkage reduction, such as the present, are justified, especially to provide information on different types of SRAs, related aspects such as capillary pressure, evaporation rates, settlement, etc.

3. Experimental program

Two high strength concretes and five conventional strength concretes were tested in this study. Measurements of crack width evolution, settlement, capillary pressure, evaporation rates and internal temperature were made for the different concretes. Drying was imposed in a chamber with forced ventilation, where the conditions for the high strength concretes were: wind temperature = 37 °C, relative humidity = 31% and wind velocity = 25 km/h; and for the conventional concretes, the conditions were: temperature = 47 °C, relative humidity = 26% and wind velocity = 26 km/h. The coefficients of variation of the wind temperature, relative humidity and velocity were 5%, 11% and 2.5%, respectively. Note that less extreme conditions had to be imposed on the high strength concrete since preliminary trials showed extensive surface cracking at higher temperatures. The drying was imposed at the age of about 50 min for the normal concretes and about 80 min for the high strength concretes. The test duration in each case was 240 min, which was fixed on the basis of preliminary trials [18]. Readings of all the quantities measured, except the evaporation rate and humidity, were taken every minute using a PC-based data acquisition system; the humidity was measured with a hand-held digital hygrometer and the evaporation rate was determined through weight loss measurements, as explained later.

3.1. Materials used

Five conventional concretes (denoted as C), with a design compressive strength of 35 MPa, were used — three with different types of SRAs available in the Spanish market, denoted as E, S and R (and with a polycarboxylate based superplasticizer, denoted as G) — and two control mixes (without any SRA) — one with the superplasticizer G and another with a melamine based superplasticizer, denoted as D. Two high strength mixes, denoted as HP, with a design compressive strength of 65 MPa, both with the superplasticizer D, without and with the SRA E, were tested. In all the concretes, European standard CEM I 52.5R cement and crushed limestone aggregates were employed. The SRA/cement dosage, by weight, was fixed as 1.5% (considering the active material) based on previous work [11–13]. For the proportioning, the aggregates were considered to be in the saturated surface-dry state within the concrete. The characteristics of the superplasticizers and SRAs used, and the mix proportions of the concretes tested are shown in Tables 1 and 2, respectively; for the concretes, the first letter after the hyphen denotes the superplasticizer used and the second letter (if any) denotes the SRA used. Note that the water content of the superplasticizers and SRAs were taken into account in the water/cement ratio.

The surface tension of the liquid phases (i.e., combination of water-superplasticizer-SRA or water-superplasticizer) of each of the concretes was determined using a Lauda tensiometer, which is based on the Du Nouy ring, according to the ASTM D971-99a standard [20]; further details can be found in [21]. In principle, each test was repeated three times; if the standard deviation of the three repetitions was above 0.25, two more trials were made. The measurements were conducted at 20, 30, 35 and 40 °C to evaluate of the effectiveness of the SRA in decreasing the surface tension of water over a range of temperatures. Figs. 1a and b shows the surface tension values for the liquid phases of the conventional and high strength mixes,

Table 2
Mix proportions of the concretes tested

Concrete		C-GE	C-GR	C-GS	C-G	C-D	HP-DE	HP-D
w/c		0.45					0.35	
kg/m^3	Cement	325					480 + 48 kg silica fume	
	Sand 0–2 mm	250					–	
	Sand 0–5 mm	740					840	
	Gravel 5–12 mm	200					921	
	Gravel 12–20 mm	725					–	
lt/m^3	Super-plasticizer	1.9	2.1	1.9	2.1	3.2	10.5	20.0
	SRA	5.4	5.6	7.5	–	–	8.0	–
	Mixing water	178.4	179.6	182.6	182.6	182.2	184.9	185.7

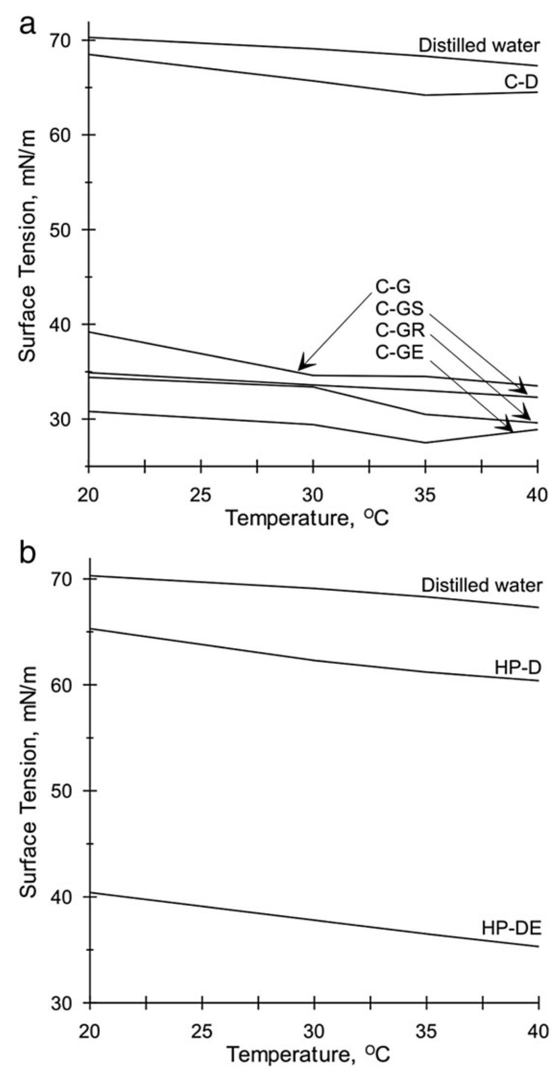

Fig. 1. (a) Surface tension data for the liquid phases of the conventional concretes. (b) Surface tension data for the liquid phases of the high strength concretes.

respectively. It is clear that the reduction in surface tension is significant in all cases and that the effectiveness of the SRA is not reduced at the higher temperatures. As seen in Fig. 1a, the surface tension of the water of the conventional concretes is reduced by half to the range of 39–28 mN/m compared with the range of 70–67 mN/m for plain water, at the temperatures considered. Interestingly, one of the superplasticizers (i.e., the polycarboxylate G) also reduces the surface tension (39–34 mN/m) similar to the SRAs while the melamine based superplasticizer D, does not have much effect on the surface tension (69 to 65 mN/m). Similarly, in the liquid phases of the high strength concretes, the SRA E reduces the surface tension to the range of 40–35 mN/m while the superplasticizer D has some effect (65 to 60 mN/m) at higher dosages.

3.2. Crack width measurement

For evaluating the evolution of surface deformation and crack widths due to restrained plastic shrinkage, a test setup was devised [18,21] by adapting those used by previous researchers [4,6,22–25]. The main objective was to have a setup where deformation would localize and lead to cracking in a well-defined cross-section and to monitor the evolution of deformation and cracking at that section. The test configuration (see Fig. 2) consists of a 600×150×150 mm metal mould adapted to anchor the concrete at the ends of the prism using steel bolts of 50 mm length and 5 mm diameter having 9 mm nuts at their embedded ends. The bottom of the mould was covered with an 8 mm thick nylon sheet in order to reduce friction and adhesion between the concrete and the mould. In the central section, a wedge that is 50 mm wide and 106 mm high is placed to act as a stress riser. To measure horizontal displacement (across the section with the stress riser), an Ω-shaped transducer, with a gage length of 100 mm and span of ±5 mm, was placed (as in Fig. 2) on the fresh concrete surface using two 100×10 mm aluminium plates with 5 mm long pins at the bottom; the measurement system was light enough (i.e., exerts a pressure of merely 0.25 kPa) to float on the surface of the concrete and yet adhere to the concrete. Previous work with the same setup [18] showed that reliable measurements of the horizontal displacement evolution could be made as the concrete surface dries, reflecting shrinkage strain initially and crack opening later. Though some aspects are similar (e.g., the stress riser, end fixity, uni-directional cracking) to that of the test setup of ASTM C 1579 [5,26], the present configuration was preferred in this study since it leads to the localization of cracking in a narrow section, which can be instrumented for continuous monitoring of crack width.

3.3. Capillary pressure measurements

In a specimen identical to that used for the crack width evolution measurement, the capillary pressure was determined, as in Fig. 3, with

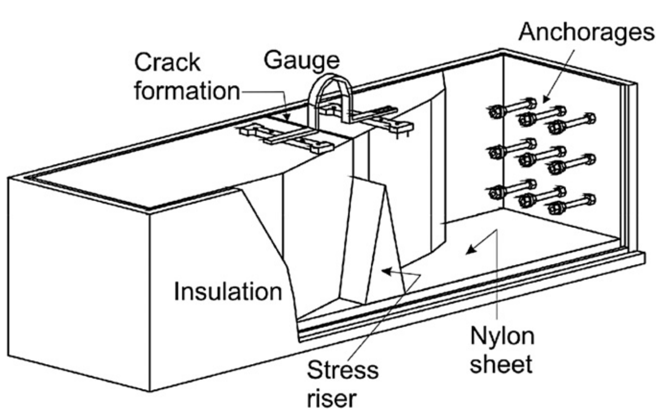

Fig. 2. Configuration for the crack width measurement.

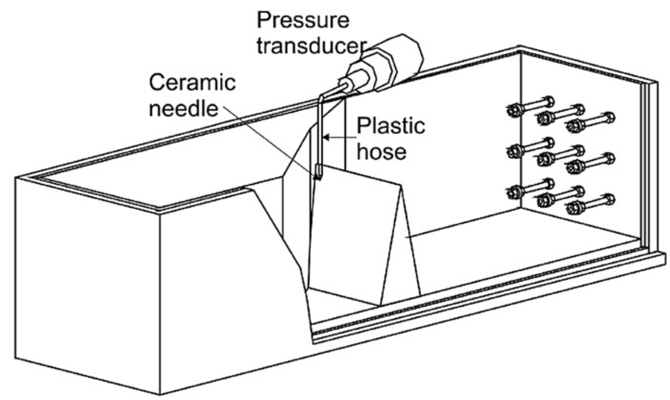

Fig. 3. Setup used for capillary pressure measurement.

a microtensiometer having a ceramic sensor tip embedded in the concrete and connected to a pressure transducer of 100 kPa capacity. The sensor was embedded at a depth of 36 mm.

3.4. Evaporation rate, settlement and internal temperature

The rate of evaporation was determined by measuring the loss in weight of water and concrete placed in pans with exposed surface areas of 220 cm^2. The weights of the pans were measured every 30 min. An LVDT was used to measure the vertical settlement by resting the transducer tip on a polymer plate placed on the surface of the specimen used to determine the capillary pressure. The internal temperature of the concrete was monitored with a thermocouple embedded at a depth of 36 mm in each of the prisms.

4. Results obtained

4.1. Basic properties of the concretes

Table 3 shows the slump, density and 28-day compressive strength data for the concretes tested. For the conventional concretes, the admixtures that decrease the surface tension had some plasticizing effect resulting in the increase in slump while the SRA addition reduced the slump in the high strength concrete. As expected, the SRAs reduce the compressive strength [12] of the concrete though the density is unaffected. It was also observed that the SRAs produced significant set retardation in conventional concretes, which is in accordance with the observations of Lura et al. [5] on mortar.

4.2. Crack width measurements

Curves showing the horizontal displacement evolutions for the different conventional concretes are given in Fig. 4. Considering the curve for the control concrete C-D, three stages can be observed with (1) an initial stage lasting for about 30 min where there is some expansion (probably corresponding to the evaporation of free surface water),

Table 3
Basic properties of the concretes tested

Concrete	Slump, mm	Density, kg/m^3	f_c, MPa
C-GE	225	2400	44.0 (±5%)
C-GR	195	2380	45.9 (±1%)
C-GS	200	2395	39.8 (±5%)
C-G	210	2400	45.1 (±4%)
C-D	180	2400	47.2 (±4%)
HP-DE	180	2380	71.5 (±2%)
HP-D	260	2400	80.9 (±4%)

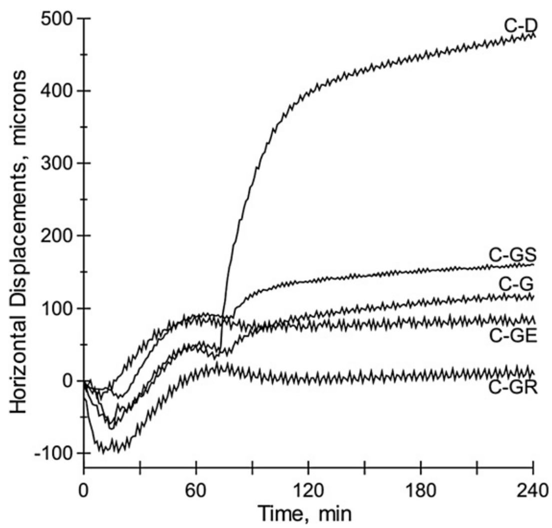

Fig. 4. Displacement evolution in the conventional concretes.

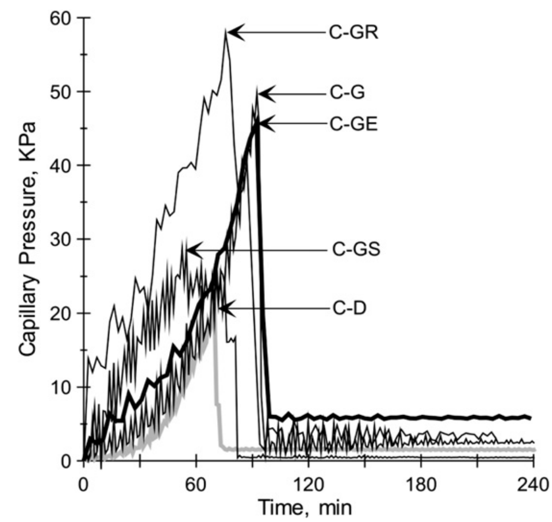

Fig. 6. Negative capillary pressure evolution in the conventional concretes.

followed by (2) a stage lasting about 30 min with increasing displacement (due to shrinkage strain) and finally (3) significant increase in displacement corresponding to the crack initiation and opening lasting about 3 h, when the final crack width is about 500 μm. These stages conform to the phases identified recently by Lura et al. [5] for plastic shrinkage corresponding to drying of bleed water, forming of minisci in the top layer and movement of the minisci to the lower layers. Interestingly, there is a well-defined kink in the curve between the second and third stages indicating the localization of the deformation and crack initiation. For the other concretes, the curves are similar in the first two stages but significantly different from that of C-D in the cracking stage. In the cases of C-G and C-GS, there is a small amount of crack opening (i.e., increase in the displacement after the kink) in the order of 100 μm. In the other two cases, of C-GR and C-GE, there is practically no crack opening. It should be noted that the concrete C-G, which has a superplasticizer that decreased the surface tension of water, behaves similar to the concretes with an SRA and even overshadows the effects of the SRAs.

The behaviour of the high strength concretes is seen in Fig. 5, where the control concrete HP-E does not exhibit the response corresponding to stages 1 and 2 of the conventional concrete but has a crack initiating almost immediately and opening to a width of about 400 μm. The concrete with the SRA (HP-DE) exhibited crack initiation at about 15 min and a final crack opening of about 100 μm.

4.3. Capillary pressures

The evolutions of the negative capillary pressure, at a depth of 36 mm, are plotted in Figs. 6 and 7 for the different concretes studied. All curves have the same trend with a gradual increase in capillary pressure at an increasing rate and then a sudden drop after the maximum suction is reached. For the conventional concretes (see Fig. 6), the peak capillary pressure values ranges from −21 to −65 kPa occurring after 50 to 90 min, which is about when the cracking initiates (or the stage 3 begins in the displacement response, see Fig. 4). This appears to indicate the critical point when the breakthrough menisci radius is reached [5,27,28]. In Fig. 7, the evolutions of the capillary pressure are shown for the high strength concretes, where the peak value of −10 kPa occurs at about 90 min for the control mix HP-D, and the peak of −34 kPa occurs at about 220 min for HP-DE.

It appears from the capillary pressure measurements that the decrease in surface tension of the aqueous solution of the concrete results in the delay of the occurrence of the maximum suction (or peak capillary pressure), which reduces the tendency for plastic shrinkage cracking [28].

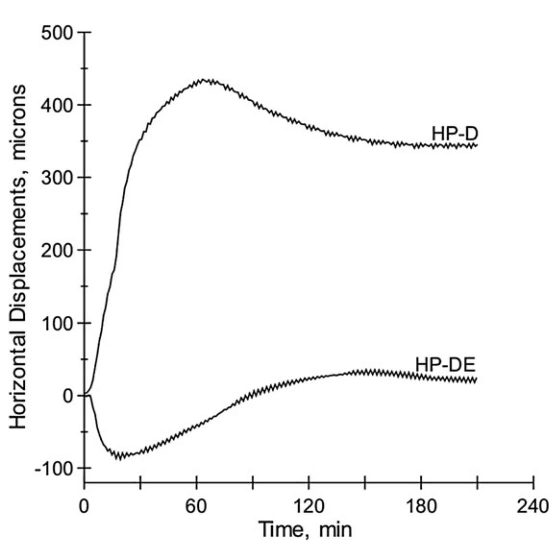

Fig. 5. Displacement evolution in the high strength concretes.

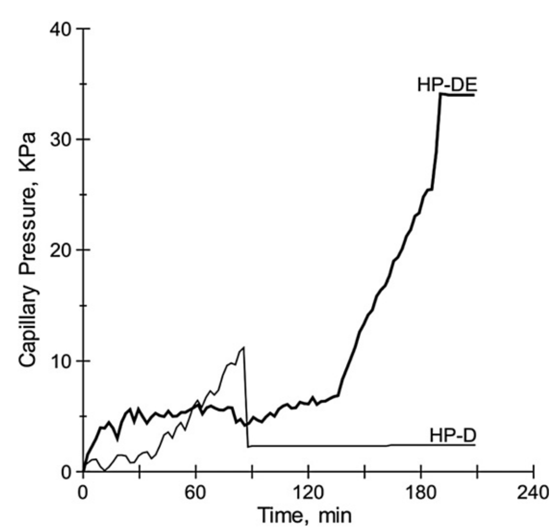

Fig. 7. Negative capillary pressure evolution in the high strength concretes.

4.4. Other complementary results

Measurements of weight loss during the induced drying showed that the evaporation rates from the free (bulk) water surface were 1.48 and 0.57 $kg/m^2/h$, respectively, for the conditions imposed on the conventional and high strength concretes. The former rate is higher than the evaporation rate of 1 $kg/m^2/hr$ above which plastic shrinkage cracking is expected to occur, and therefore cracking in the conventional concretes is justified. However, though the evaporation rate imposed on the high strength concretes is much lower, cracking does occur, reflecting the tendency for considerable plastic shrinkage caused by the high fines content and low water/binder ratio.

The evaporation rates from the concrete surfaces are initially in the same range as that of the free water surface until about 30 min, after which the rate slowly decreases, indicating the end of the removal of the water from the concrete surface [5]. The conventional concretes with admixtures that lower the surface tension showed much lower evaporation rates than the control mix C-D. However, there was no such difference in evaporation rates between the high strength concretes.

The measurements of the surface settlement showed that there was subsidence occurring at almost a constant rate in the conventional concretes up to about 30 min after which the response gradually flattens and ceases to increase beyond 90 min. The final settlement values for the concretes C-D, C-G and C-GR were about 600 µm while the settlements for C-GE and C-GS were about 500 and 200 µm, respectively. In the high strength concretes, the settlements increased linearly until about 90 min in HP-D and until about 60 min in HP-DE, and then flattened out to reach the final values of 500 µm and 250 µm, respectively.

The internal temperatures measured at a depth of 36 mm showed that there is a linearly increasing temperature within the concrete. Initially, all the concretes were at a temperature of about 22 °C and subsequently experienced an increase of 12–20 °C in the conventional concretes and an increase of 4–8 °C in the high strength concretes. The lowest increments were seen in the control mixes, i.e., in the concretes without the surface tension reducing admixtures (C-D and HP-D), which is in accordance with the observations of temperature change in mortars with and without an SRA made by Lura et al. [5].

5. Discussion of the results

Considering the results obtained here and the model used by Lura et al. [5], the behaviour of concrete during plastic shrinkage cracking can be further explained as follows. First, when there is evaporation of bleed water, (1) there is no shrinkage but some expansion could occur, (2) the evaporation rate is the same as that from bulk water, (3) there is only a slight increase in the negative capillary pressure and (4) the settlement increases linearly. In the second phase, where the menisci form in the top layers, there is (1) a gradual increase in shrinkage strain, (2) the evaporation rate deviates from that of bulk water and decreases, (3) the negative capillary pressure increases almost linearly, and (4) the rate of settlement decreases. In the final phase, where the menisci form in the lower layers, there is (1) a gradual increase in shrinkage crack width, (2) the evaporation rate decreases significantly, (3) the negative capillary pressure reaches a peak and drops, and (4) further settlement stops. The critical point between the second and third phases is reached when the negative capillary pressure peaks as the menisci reach a breakthrough radius inducing stresses higher than the local tensile strength, causing strain localization and crack initiation. This is manifested as a kink in the displacement curves after which the third stage corresponding to crack opening occurs. The different phases are more clearly observed in the conventional concretes but not in the high strength concretes.

In both the conventional and high strength concretes, the beneficial influence of the reduction of surface tension of the liquid phase on plastic shrinkage is evident from the results. When the surface tension is decreased to about half that of plain water, there is a substantial decrease in the plastic shrinkage crack width, settlement and evaporation rate, and an increase in the time at which the peak capillary pressure occurs in the concrete. It can be stated that the presence of an SRA, or even a superplasticizer that decreases the surface tension of the mixing water significantly, decreases the driving forces (or the potential) for plastic shrinkage cracking [5] due to the lowering of the evaporation rate and delay in the occurrence of the maximum suction in the capillary pores, and reduction of settlement. It is also possible that there is a decrease in the early autogenous shrinkage as observed in hardened concrete [12], which will further mitigate cracking.

In high strength concrete, there is clearly a higher tendency for plastic shrinkage and settlement, as confirmed in this study, even at relatively low evaporation rates. Cracking could consequently be initiated at lower negative capillary pressures and less adverse environmental conditions than in conventional concrete. Nevertheless, the incorporation of an SRA decreases the cracking potential significantly possibly by delaying the peak capillary pressure.

6. Conclusions

In both conventional and high strength concretes, the decrease in the surface tension of the mixing water (i.e., the liquid phase) through the incorporation of an SRA, or a suitable superplasticizer, can reduce plastic shrinkage cracking substantially by lowering the evaporation rate, delaying the peak capillary pressure due to the development of menisci in the pores and decreasing settlement.

The monitoring of displacements continuously during drying through the use of an appropriate test setup has facilitated the identification of the different stages of plastic shrinkage. It is evident that there is no shrinkage until the surface water has evaporated after which the shrinkage strain increases until the capillary stress peaks and the crack initiates. Further evaporation leads to the opening of the crack until the concrete hardens after about 6 h (under the conditions of the present work). The critical point is reflected as a kink in the displacement–time curve indicating strain localization and crack initiation.

Acknowledgements

Partial financial support from the Spanish CICYT grant PB98-0928, and the FEDER 2FD97-1973-C0202 grant from the Spanish CICYT and the European Commission is gratefully appreciated. The first author thanks the Mexican CONACYT for funding his doctoral studies at the UPC. Materials used in the study were donated by BASF Construction Chemicals, Cementos Molins and W.R. Grace.

References

[1] D. Ravina, R. Shalon, Plastic shrinkage cracking, ACI Mater. J. (1968) 282–292.
[2] M.D. Cohen, J. Olek, W. Dolch, Mechanism of plastic shrinkage cracking in portland cement and portland cement–silica fume paste and mortar, Cem. Concr. Res. 20 (1990) 103–119.
[3] I. Padron, R.F. Zollo, Effect of synthetic fibers on volume stability and cracking of portland cement and mortar, ACI Mater. J. 87 (4) (1990) 327–332.
[4] A.A. Almusallam, M. Abdul-Waris, M. Maslehuddin, S. Al-Gahtani, Placing and shrinkage at extreme temperatures, Concr. Int. 21 (1) (1999) 75–79.
[5] P. Lura, B. Pease, G.B. Mazzotta, F. Rajabipour, J. Weiss, Influence of shrinkage-reducing admixtures on development of plastic shrinkage cracks, ACI Mater. J. 104 (2) (2007) 187–194.
[6] P. Soroushian, S. Ravanbakhsh, Control of plastic shrinkage cracking with specialty cellulose fibers, ACI Mater. J. 95 (4) (1998) 429–435.
[7] J. Mora, R. Gettu, C. Olazábal, M.A. Martín, A. Aguado, Effect of the incorporation of fibers on the plastic shrinkage of concrete, in: P. Rossi, G. Chanvillard (Eds.), Fibre-Reinforced Concretes (FRC), Proc. Intnl. Symp. BEFIB'2000 (Lyon, France), RILEM Publications S.A.R.L., Cachan, France, 2000, pp. 705–714.
[8] K.J. Folliard, N.S. Berke, Properties of high-performance concrete containing shrinkage-reducing admixture, Cem. Concr. Res. 27 (9) (1997) 1357–1364.
[9] A. Balogh, New admixture combats concrete shrinkage, Concr. Constr. 41 (7) (1996) 546–551.

[10] D.P. Bentz, M.R. Geiker, K.K. Hansen, Shrinkage-reducing admixtures and early-age desiccation in cement pastes and mortars, Cem. Concr. Res. 31 (2001) 1075–1085.
[11] R. Gettu, J. Roncero, On the long-term response of concrete with a shrinkage reducing admixture, in: R.K. Dhir, P.C. Hewlett, M.D. Newlands (Eds.), Admixtures — Enhancing Concrete Performance (Proc. Intnl. Conf., Dundee, UK), Thomas Telford, London, 2005, pp. 209–216.
[12] J. Roncero, R. Gettu, M.A. Martín, Evaluation of the influence of a shrinkage reducing admixture on the microstructure and long-term behavior of concrete, in: V.M. Malhotra (Ed.), Proc. Seventh CANMET/ACI Intnl. Conf. on Superplasticizers and Other Chemical Admixtures in Concrete (Berlin), Supplementary papers, 2003, pp. 207–226.
[13] R. Gettu, J. Roncero, M.A. Martín, Long-term behaviour of concrete incorporating a shrinkage-reducing admixture, Indian Concr. J. 76 (9) (2002) 586–592.
[14] M. Shoya, S. Sugita, T. Sugiwara, Improvement of drying shrinkage and shrinkage cracking of concrete by special surfactant, in: E. Vázquez (Ed.), Admixtures for Concrete: Improvement of Properties, Chapman and Hall, London, 1990, pp. 484–495.
[15] S.P. Shah, M.P. Karaguler, M. Sarigaphuti, Effects of shrinkage reducing admixture on restrained shrinkage cracking of concrete, ACI Mater. J. 89 (3) (1992) 88–90.
[16] W.J. Weiss, N.S. Berke, Admixtures for reduction of shrinkage and cracking, in: A. Bentur (Ed.), Early Age Cracking in Cementitious Systems, RILEM Report, vol. 25, 2003, pp. 323–338, Chapter 7.5.
[17] W.J. Weiss, W. Yang, S.P. Shah, Shrinkage cracking of restrained concrete slabs, ASCE J. Eng. Mech. 124 (7) (1998) 765–774.
[18] J. Mora, M.A. Martín, R. Gettu, A. Aguado, Study of plastic shrinkage cracking in concrete and the influence of fibers and a shrinkage reducing admixture, in: V.M. Malhotra (Ed.), Proc. Fifth CANMET/ACI Intl Conf on Durability of Concrete (Barcelona, Spain), Supplementary Papers, 2000, pp. 469–483.
[19] J. Mora, A. Aguado, R. Gettu, The influence of shrinkage reducing admixtures on plastic shrinkage, Mat. Constr. 53 (271) (2003) 71–80.
[20] ASTM D 971, Standard Test Method for Interfacial Tension of Oil Against Water by Ring Method, ASTM International, West Conshohocken, Pa., USA, 2001.
[21] J. Mora, Study of restrained plastic shrinkage cracking in conventional and high performance concretes, Doctoral Thesis, ETSECCPB, Universitat Politècnica de Catalunya, Barcelona, Spain, 2002.
[22] P. Balaguru, Contribution of fibers to crack reduction of cement composites during the initial and final setting period, ACI Mater. J. 91 (3) (1994) 280–288.
[23] N.S. Berke, M.P. Dallaire, The effect of low addition rated of polypropylene fibers on plastic shrinkage cracking and mechanical properties of concrete, in: J.I. Daniel, S.P. Shah (Eds.), Fiber Reinforced Concrete: Developments and Innovations, ACI SP-142, 1994, pp. 19–42.
[24] A. Nanni, D.A. Ludwig, M.T. McGills, Plastic shrinkage cracking of restrained fiber-reinforced concrete, Transp. Res. Rec. 1382 (1991) 69–72.
[25] K. Yokoyama, S. Hiraishi, Y. Kasai, K. Kishitani, Experimental study of shrinkage and cracking of flowing concrete at early ages, JCA Proc. Cem. Concr. 50 (1996) 588–593.
[26] ASTM C 1579, Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert), ASTM International, West Conshohocken, Pa., 2006
[27] T.A. Hammer, Effect of silica fume on the plastic shrinkage and pore water pressure of high-strength concretes, Mat. Struct. 34 (2001) 273–278.
[28] A. Kronloff, Experimental study on the basic phenomena on shrinkage and cracking of fresh mortar, Cem. Concr. Res. 25 (8) (1995) 1747–1754.