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INVESTIGATION OF EARLY AGE DEFORMATION IN SELF-COMPACTING CONCRETE

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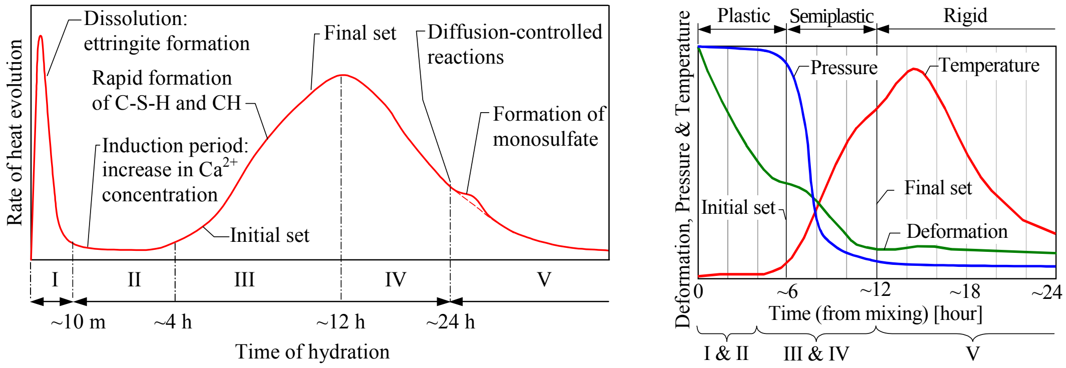
Abstract

In the presented work, early age (< 24 h) autogenous deformation was measured and crack tendency due to plastic shrinkage was evaluated; see Esping and Löfgren [1]. For the autogenous deformation, a specially developed digital dilatometer was used which generated accurate measurements of the linear displacements of the concrete, which was cast in a vapour-proof flexible tube mould. The plastic shrinkage cracking tendency was evaluated by exposing concrete specimens to early drying conditions while these were restrained by an inner steel ring. A large number of different SCC constituents and mix compositions have been investigated: e.g. w/c-ratio from 0.38 to 0.67, silica fume, and different admixtures. For comparison, tests with standard concrete were also made. The influence of different constituents and mixes on the autogenous deformation and plastic shrinkage crack tendency was observed. The results indicated that a high crack tendency arose when there was: large autogenous shrinkage (silica addition, low w/c, high fineness); high water evaporation (high w/c, low fineness); retardation (retarder or high superplasticizer dosage); low content of coarse aggregate. Minimum crack tendency was found at w/c 0.55.

1. INTRODUCTION

At early age, when the cement paste is young and has poorly developed mechanical properties, autogenous and drying shrinkage – both incorporated in the plastic shrinkage – are the two main driving forces for cracking. Generally, plastic shrinkage is usually defined as the shrinkage of fresh concrete, exposed to drying, that takes place during the time when the concrete is ‘plastic’, the duration is usually short (< 8 to 12 hours) and ends when the concrete has reached its final set. In traditional concretes plastic shrinkage cracking is mainly caused by the loss of water from the fresh concrete, e.g. by evaporation of water, which generates negative capillary pressures; this cause the paste to contract (see Wittmann [2]), which in turn can lead to cracks. These contracting capillary forces are in reverse ratio to the meniscus radius, and hence the capillary tension stresses increase with decreasing interparticle spaces. For a concrete where evaporation is prevented, a negative capillary pressure will also develop, but only once the hydration commences and the concrete sets. To avoid this type of cracks, care has to be taken to protect the surface against drying. However, experience in the use of concretes with low w/b has revealed that severe cracking may occur in spite of proper protection (curing membrane, etc). Conditions such as reduced maximum aggregate size, presence of retarding admixtures, increased binder content, and deficient curing all contribute to this problem. Early cracking is usually observed in the period soon after casting up to 6-8 hours later, depending on the concrete temperature, material composition, weather conditions and the degree of retardation. In this early phase, the rheology of concrete changes dramatically as the concrete sets, i.e. it changes from a liquid to a solid behaviour within some hours. At the same time the tensile strain capacity goes through a minimum. The cause of this change in rheology is the hydration of Portland cement, which is a complex sequence of chemical reactions leading to setting and hardening. Immediately after mixing cement and water, reactions start to occur and these generate an outburst of heat (Stages I in Figure 1). After these initial stages an induction period, or dormant period, is entered (Stage II). During the induction period not much hydration takes place, but this does not mean that the paste is ‘dormant’ with respect to volume changes.

Setting (during Stage III) is defined as the onset of rigidity in fresh concrete, and the period of fluidity, preceding setting, corresponds to the induction period (Stage II); see Figure 1(a). As long as the concrete is fluid, there will be a linear relationship between the linear shrinkage and the volumetric chemical shrinkage. However, once the self-supporting skeleton starts to form, the chemical shrinkage will mainly result in internal voids and the linear deformation diverges from the chemical shrinkage. It has been suggested (e.g. by Barcelo [4]) that, when measuring the linear deformation, the setting will be manifested as a change of the slope of the deformation; see Figure 1(b). Furthermore, once the internal voids are created it leads to the development of a capillary underpressure in the skeletal structure, see Figure 1(b), which causes an external deformation of the hardening concrete. It can be argued that the deformation occurring when the concrete is plastic may have little consequence for the risk of cracking, while the shrinkage taking place when the concrete is semiplastic is considerably more detrimental as the concrete at this stage has poorly developed mechanical properties (low tensile strength and strain capacity).



(a) (b)

Figure 1: (a) Heat evolution during hydration (based on [3]) and (b) early-age linear autogenous deformation of concrete and the corresponding development of temperature and capillary pore pressure (from [1]).

2. TEST METHODS

2.1 Autogenous shrinkage test method

In this study, autogenous linear deformation was monitored by a new test method, the concrete digital dilatometer (CDD), developed in order to start measurement before setting, when concrete is fresh, as well as for the hardening concrete. The method is a modification of the CT1 digital dilatometer for pastes and mortars [5]. The CDD sample consists of a concrete specimen, cast in a steel coil reinforced 0.4 mm thick vapour-proof flexible polyurethene (PU) tube with inner diameter of 82 mm and specimen length ~400 mm, sealed with a pair of hose clamps and 30 mm thick PVC end-caps equipped with O-ring sealing. The mould was placed in a mechanical stable measuring rig, where a digital gauge recorded the unrestrained linear deformation with an accuracy of 0.003 mm. The test was performed in a thermostable room at 20ºC, where the measurement recording was started at 30 minutes from water addition. The equipment and apparatus for a typical test are shown in Figure 2, and for each test three complete CDD set-ups were used. The experiments have also been supplemented with measurements of temperature and pore pressure in sealed specimens.

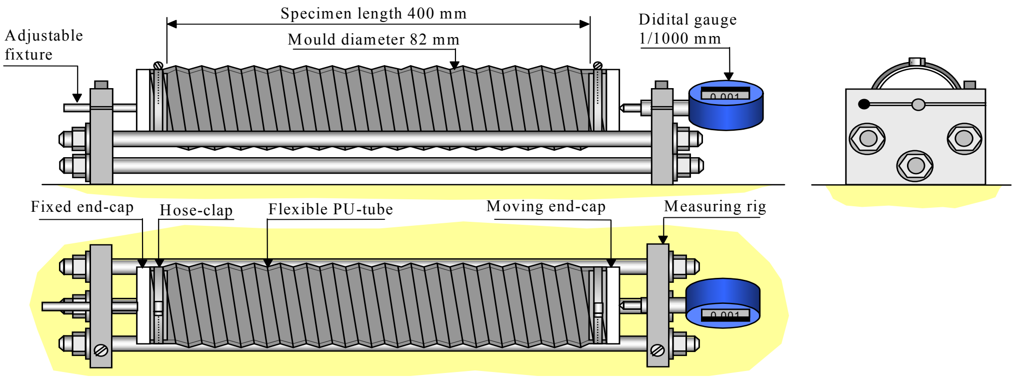


Figure 2: Test arrangement of the Concrete Digital Dilatometer (CDD) for linear autogenous deformation measurement (from [1]).

2.2 Plastic shrinkage cracking test method

The method used is intended for determination of the cracking tendency of concrete at early ages (developed by Johansen and Dahl; see [6] and [7]) but does not separate between cracks formed before or after final setting. The variability (or scatter) of the test method is relatively high; for one test series (three samples) the coefficient of variation is in the range of 20 % to 50 % and the repeatability is in the same order (for three repeated series). In the test, the fresh concrete is cast between two concentric steel rings and the specimen is then placed under an air funnel, creating an air velocity of 4.5 m/s over a fresh concrete surface; see Figure 3. The crack sensitivity is expressed as a crack index, see Figure 3, and both the temperature and the weight loss of the specimens are continuously recorded. The measurements started 60 minutes after mixing. After 20 hours of drying, the rings were taken out of the rig and the crack index was measured as the average total crack area (crack length × crack width) on the concrete surface of each of the three specimens. The crack width was measured with a crack microscope (to an accuracy of 0.05 mm) and the crack length was measured with a digital measuring wheel (to an accuracy of ±1 mm).

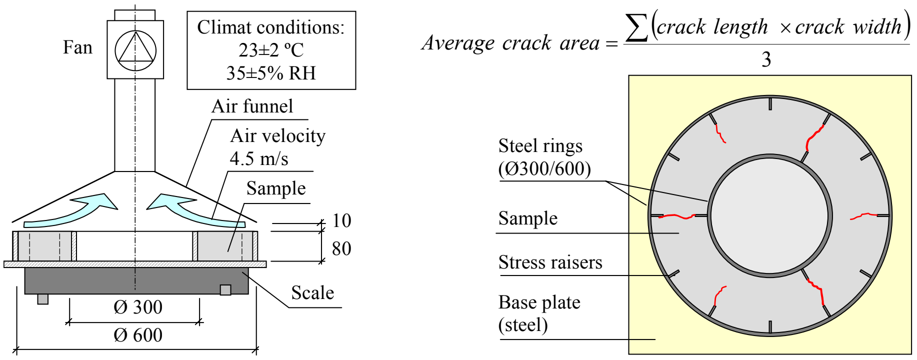


Figure 3: Test arrangement for the determination of the cracking tendency (from [1]).

3. EXPERIMENTAL PROGRAM

3.1 Materials

The mix design and its constituents, as used in this study, comprise typical materials and compositions for self-compacting concrete (SCC) in Sweden. The properties of the dry materials and admixtures are listed in Table 1 and Table 2. The concretes were prepared in batches of 40 or 60 liters, mixed in a twin-shaft paddle mixer for 4 minutes after water was added to the premixed dry materials. The admixtures were added directly after the water.

Table 1: Properties of dry materials (cement, silica, filler and aggregate).

ID	Type	Product name	Supplier	Density [kg/dm^3]
C	CEM II/A-LL 42.5R	Byggcement, Skövde	Cementa	3 080
SF	Silica fume	Microsilica	ELKEM	2 250
F	Ground limestone	Limus 40	NordKalk	2 670
A 0-4	Natural aggregate	Sjögärde	Färdig Betong	2 670
A 0-8	Natural aggregate	Hol	Färdig Betong	2 650
A 8-16	Crushed aggregate	Kungälv	Färdig Betong	2 700

Table 2: Properties of admixtures.

ID	Type	Product name	Supplier	Density [kg/dm^3]	Dry content [weight%]
SP	Super plasticizer (polycarboxylate ether)	Sikament 56	SIKA	1 100	37 %
ACC	Accelerator (sodium)	SikaRapid-1	SIKA	1 200	37 %
RE	Retarder (polyalkyl ether)	SikaRetarder	SIKA	1 200	27 %
SRA	Shrinkage-reducer (polymeric glycol)	SikaControl-40	SIKA	1 000	–

In order to evaluate the effect of constituent type and dosage, a number of different mixes were investigated. The following mixes are presented in this paper (for the full experimental study see [1]):

1. Reference concretes: w/c 0.38, 0.45, 0.55 and 0.67 (see Table 3).
2. Silica fume: 5% and 10% SF by cement weight (SF replaced equal C volume).

3. Coarse aggregate content: 20%, 30%, 40% (REF) and 50% A 8-16 of total volume of aggregate. The changes were replaced by equal volume of A 0-8.
4. Superplasticizer dosage: 0.6%, 0.8% (REF) and 1.0% SP dosage of C weight.
5. Accelerator and retarder: 1.5% ACC and 0.2% RE by C weight.
6. Shrinkage-reducing admixture: 1.0% and 2.0% SRA by C weight.
7. Conventional concrete: w/c 0.55 with 345 kg cement and 60/40% (0-8 mm/8-16 mm) aggregate; and w/c 0.67 with 330 kg cement and 60/40% (0-8 mm/8-16 mm) aggregate.

Table 3: Recipe of SCC reference mixes in kg/m^3.

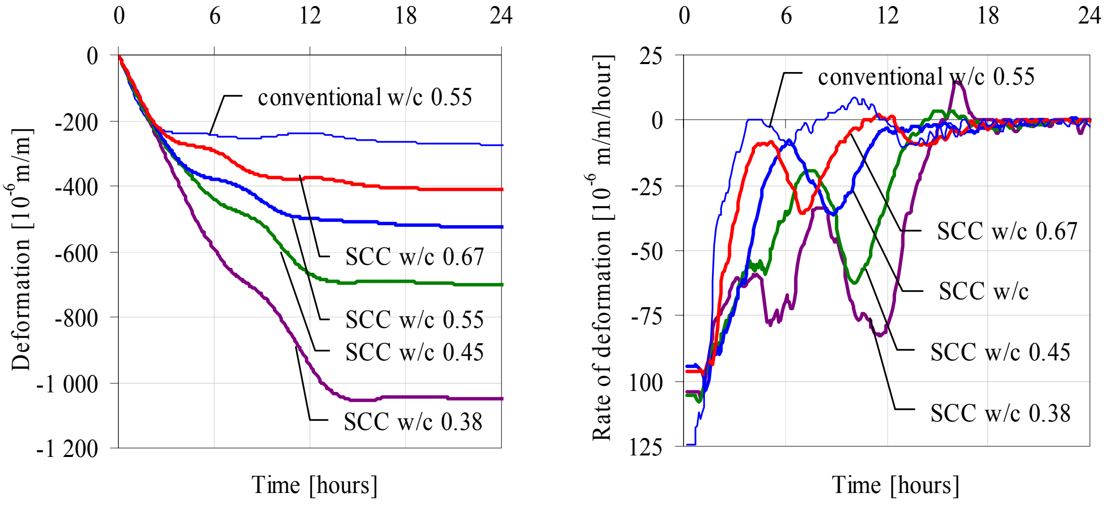
ID	w/c 0.38	w/c 0.45	w/c 0.55	w/c 0.67
C	420	380	340	300
W	160	171	187	200
A 0-4	0	0	81	155
A 0-8	1021	998	879	771
A 8-16	694	678	651	628
F	40	100	160	220
SP	7.6 (1.8%C)	5.7 (1.5%C)	4.1 (1.2%C)	2.4 (0.8%C)

4. RESULTS

4.1 Autogenous deformation

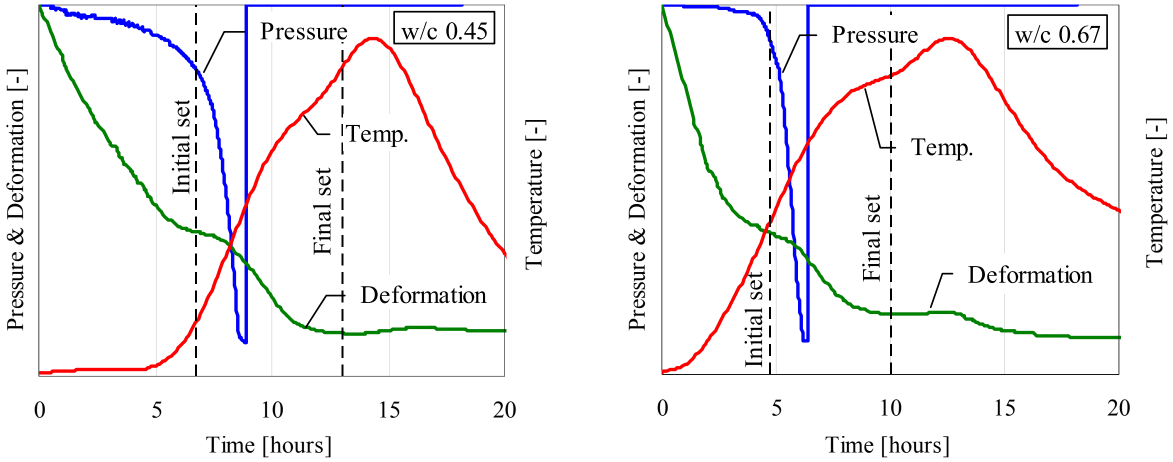
The results of the autogenous deformation measurements for the reference concretes and one conventional concrete are presented in Figure 4(a), while Figure 4(b) shows the rate of the deformation. As can be observed, increased cement content (lower w/c) increased both the total chemical shrinkage and its rate, and thereby the total autogenous deformation. Increased cement content (lower w/c) also increased the autogenous deformation and its rate in the semiplastic period (between initial and final set). Finally, increased superplasticizer addition had a delaying and retarding effect on the hydration and thereby extends all the time to the initial and final set.

Furthermore, Figure 5 shows the relationship between the development of deformation, temperature, and pore pressure for the concretes with w/c 0.45 (a) and w/c 0.67 (b). As can be seen, as long as the concrete is plastic the deformation develops with almost a linear relationship and, during this period, the temperature and capillary pore pressure undergo only small changes, which are linear. However, at one stage (at about five hours for w/c 0.67 and seven hours for w/c 0.45) the rate of the deformation is slowed down, indicating ‘setting’ of the concrete, and a knee point is reached. At this point in time, it can be seen that both the capillary pore pressure and the temperature reach an accelerating phase, which indicates that the dormant period is ended and that the cement hydration accelerates. Final set is reached at about 10 hours for w/c 0.67 and 13 hours for w/c 0.45, which for the deformation is manifested in a plateau slightly ahead of the temperature peak.



(a) (b)

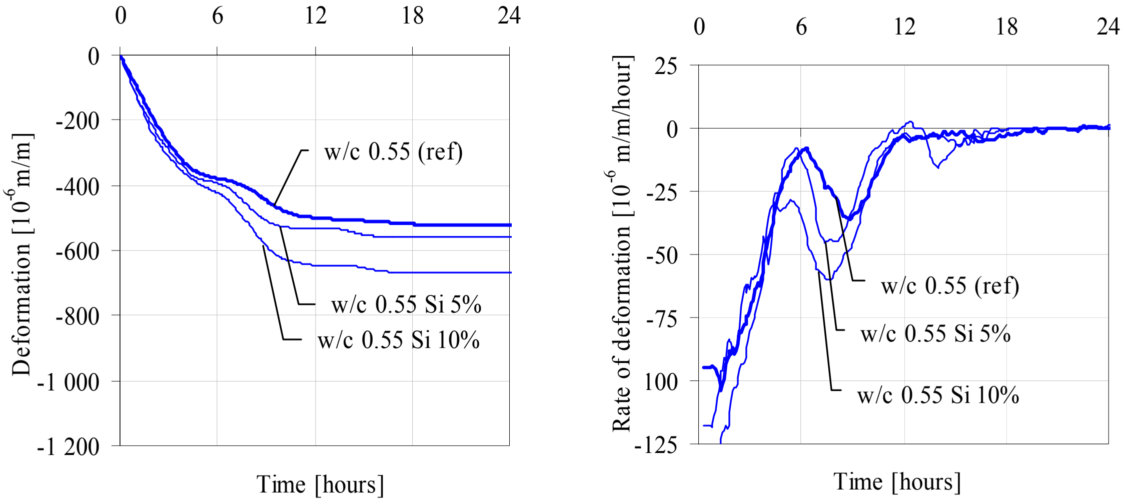
Figure 4: Autogenous deformation of self-compacting concrete with w/c from 0.38 to 0.67 (a) and (b) rate of deformation (from [1]).



(a) (b)

Figure 5: Development of temperature, capillary pore pressure, and autogenous deformation (the axes have been normalized against maximum values): (a) for concrete with w/c 0.45; and (b) for concrete with w/c 0.67 (from [1]).

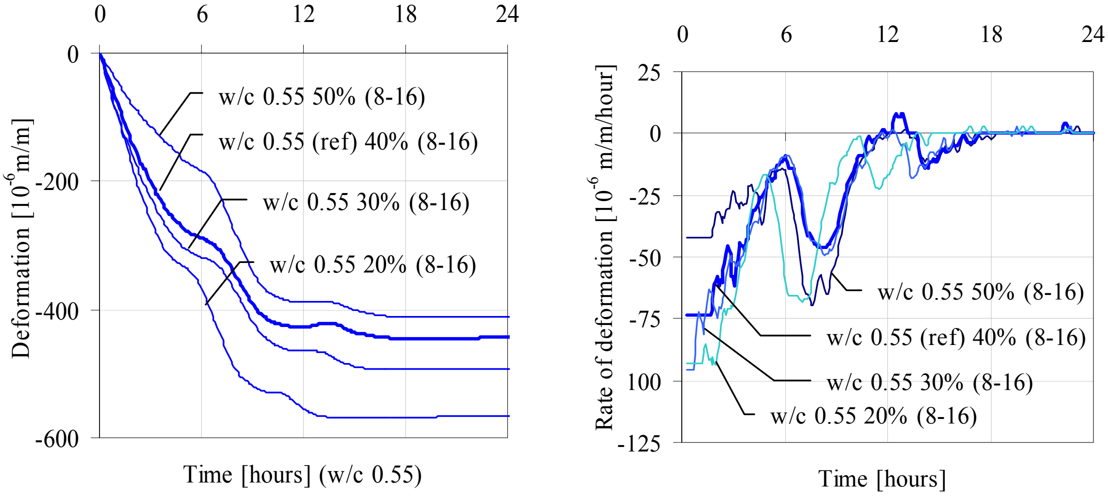
It is well known that silica fume increases the autogenous shrinkage, as well as accelerating the early hydratation and initiating the stiffness at earlier age. The results of the autogenous deformation measurements for the concretes with silica fume are presented in Figure 6. These results indicate that addition of silica fume increased the magnitude and rate of autogenous shrinkage in all periods (in the plastic, semiplastic, and rigid periods), and the effect increased with increased silica dosage. Silica fume decreased the plastic time period, and the effect increased with increased silica dosage. No changes in semiplastic time could be observed.



(a) (b)

Figure 6: Effects of silica fume (Si) on: (a) the autogenous deformation of self-compacting concrete with w/c from 0.55 and (b) the rate of deformation (from [1]).

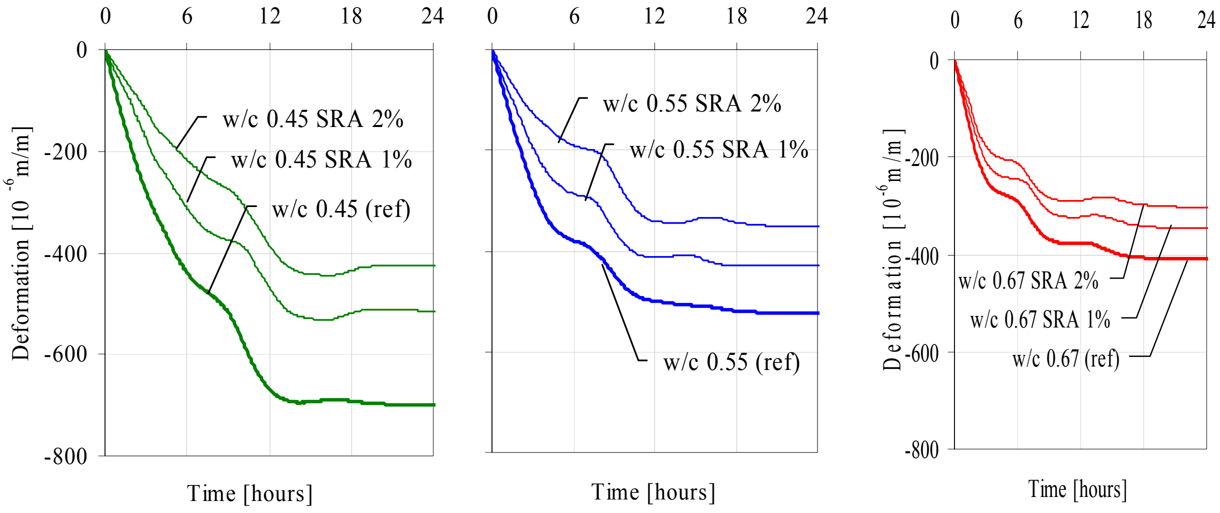
The results for the concrete with varying coarse aggregate content are presented in Figure 7. It should be noted that the content of coarse aggregate had a large impact on the rheology, which can be deduced from the aggregate packing. Good packing improves the flowability as more water is made available for dispersing the particles. The results indicate that increased coarse aggregate content decreased both the magnitude and rate of autogenous deformation. The effect was more apparent at higher content of coarse aggregate, which might be explained by the coarser particles' ability to create a restraining matrix. No significant changes in times for the plastic and semiplastic periods could be observed, but an increased content of coarse aggregate tended to delay the rigid period.



(a) (b)

Figure 7: Effects of coarse aggregate content (8-16) on: (a) the autogenous deformation and (b) the rate of deformation (from [1]).

The results of the autogenous deformation measurements for the concrete with shrinkage reducing admixture (SRA) are presented in Figure 8. The results indicate that addition of SRA decreased the magnitude and rate of autogenous shrinkage for all concretes, and the effect increased with increased SRA dosage. In the semiplastic period the effect of SRA was not as pronounced as in the plastic and rigid periods. SRA showed no effect on the times of the plastic and semiplastic periods.

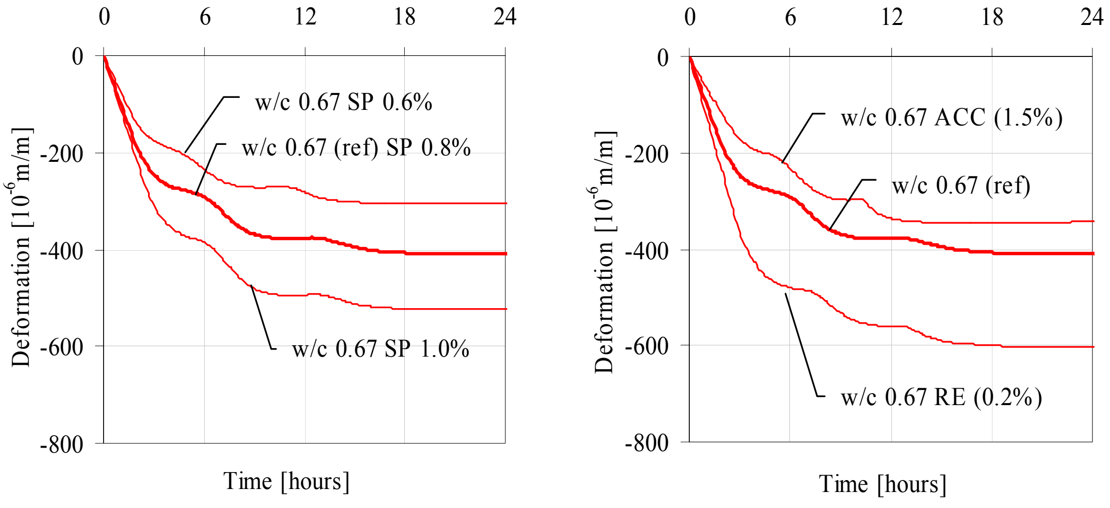


(a) (b) (c)

Figure 8: Effect of the addition of shrinkage-reducing admixture (SRA) on autogenous deformation: (a) for w/c 0.45, (b) for w/c 0.55, and (c) for w/c 0.67 (from [1]).

It is well known that SP retards the concrete, as it delays the early hydration and initiates the stiffness at higher age. The results of the autogenous deformation measurements clearly verify these phenomena, as can be seen in Figure 9(a). The results indicate that with increased SP dosage the magnitude of autogenous shrinkage increased, which can be explained by improved cement dispersion; see Holt [8]. An increased SP dosage also increased the rate of shrinkage in the plastic and semiplastic periods. After setting, the effect was the opposite, where the rate of shrinkage decreased with SP dosage. Moreover, an increased SP dosage prolonged the plastic time period, while no changes in the semiplastic time could be observed.

The results of the autogenous deformation measurements for the concrete with accelerator (ACC) and retarder (RE) are presented in Figure 9(b). The results indicate that in the plastic period (before initial setting), the accelerator increased the magnitude and rate of shrinkage while the retarder hade the opposite effect, which could be expected. In the semiplastic period, the accelerator and retarder showed no significant effect on magnitude and rate of shrinkage. In the rigid period, both the accelerator and retarder increased the rate of shrinkage. The accelerator tended to shorten the time to initial setting while the retarder tended to delay it. According to the supplier (SIKA), RE will have a small delaying effect at early hydration (to initial setting), and ACC will have no effect in the same period. The results in this study showed the same tendency.

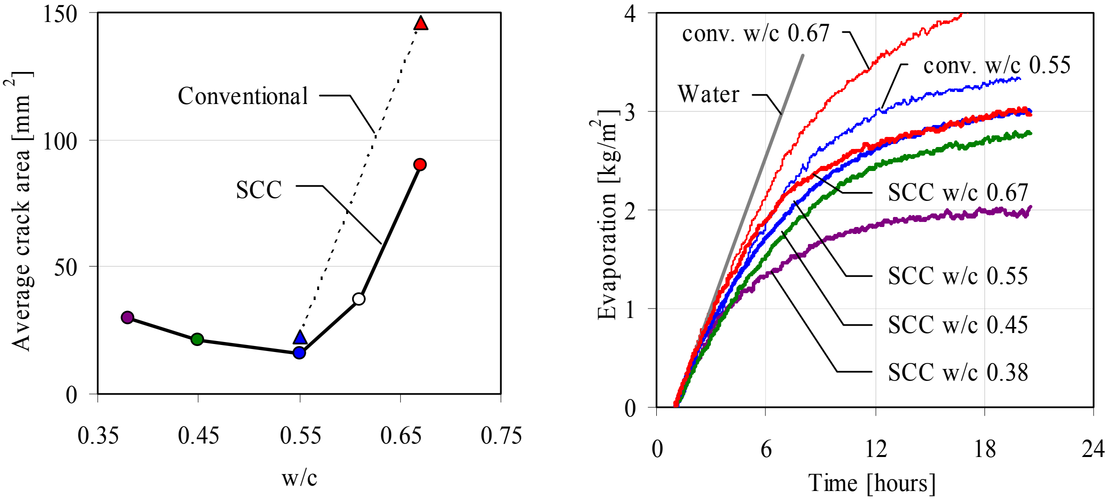


(a) (b)

Figure 9: Autogenous deformation of concrete with w/c 0.67: (a) effect of superplasticizer dosage (SP) 0.6%, 0.8%, and 1.0%; and (b) effect of accelerator (ACC) and retarder (RE) (from [1]).

4.2 Plastic shrinkage cracking

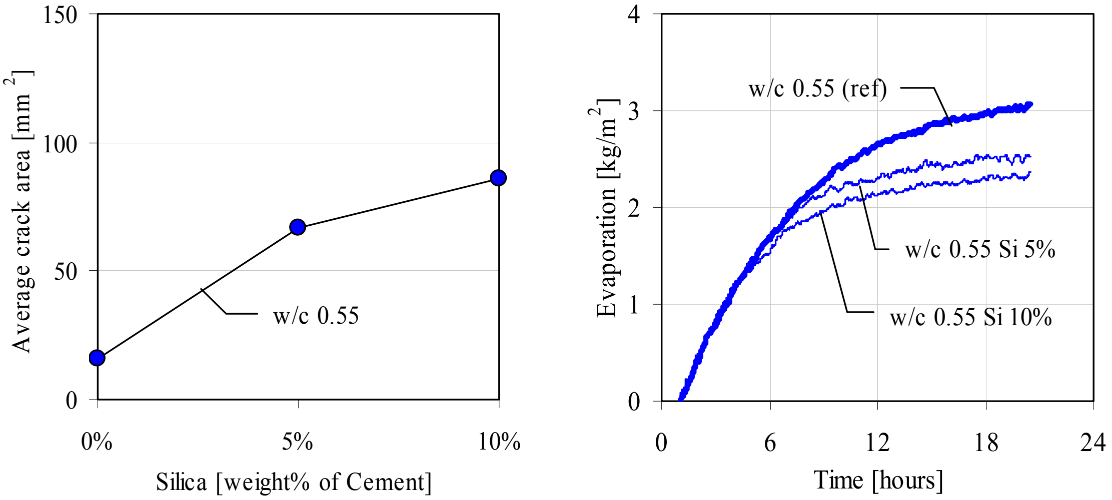
The results for the average crack area for the reference concretes are presented in Figure 10(a). As can be seen, it is evident that the concrete with the high w/c-ratio (0.67) had the highest crack area and that the concrete with w/c 0.55 had the smallest crack area. Furthermore, there seems to exist an optimum w/c-ratio for the investigated reference mixes, which indicates that the w/c-ratio should be in the region of 0.55. The conventional concrete had a higher crack area for both the tested w/c values. Evaporation curves for the concretes are presented in Figure 10(b) where it can be seen that the evaporation is higher for a concrete with a high w/c and lower for a low w/c. Moreover, the conventional concrete had a significantly higher evaporation, which could explain the increased cracking susceptibility. The initial rate of evaporation (before initial setting) for the investigated concretes varied between 0.37 and 0.44 kg/m^2/h (the low values for w/c $\leq$ 0.45); this can be compared with the evaporation from a free water surface of 0.50 kg/m^2/h for the test conditions used in this study.



(a) (b)

Figure 10: Influence of w/c ratio on: (a) the crack susceptibility and (b) the evaporation (from [1]).

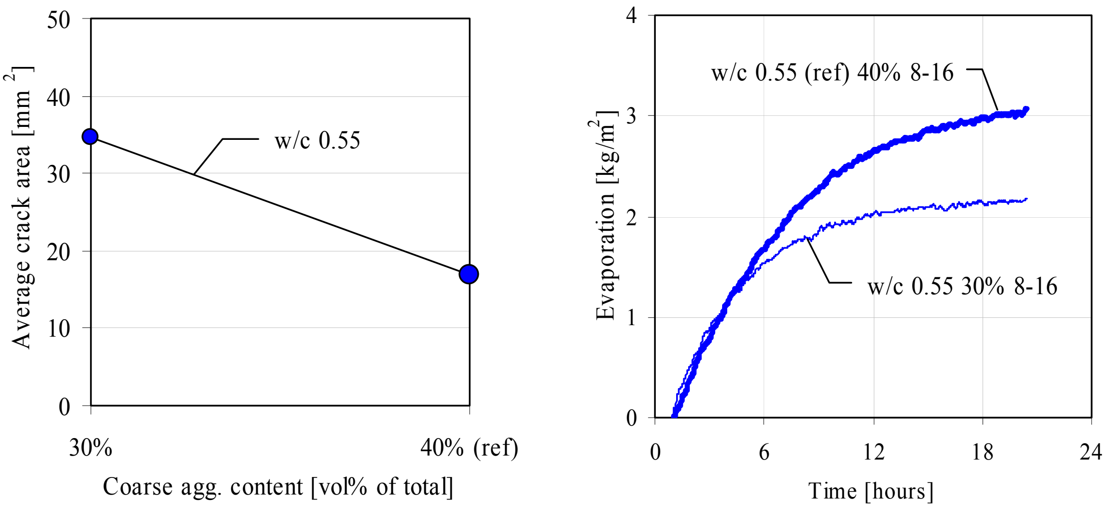
When silica fume replaced 5% and 10% of the cement in the concrete with w/c 0.55, the average crack area, which can be seen in Figure 11(a), increased dramatically. The effect that silica fume had on the evaporation can be seen in Figure 11(b). Silica reduced the evaporation. A possible explanation for the increased crack area is an increased amount of small particles, which increased the autogenous shrinkage, as could be seen in the CDD experiments.



(a) (b)

Figure 11: Influence of silica fume (Si) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

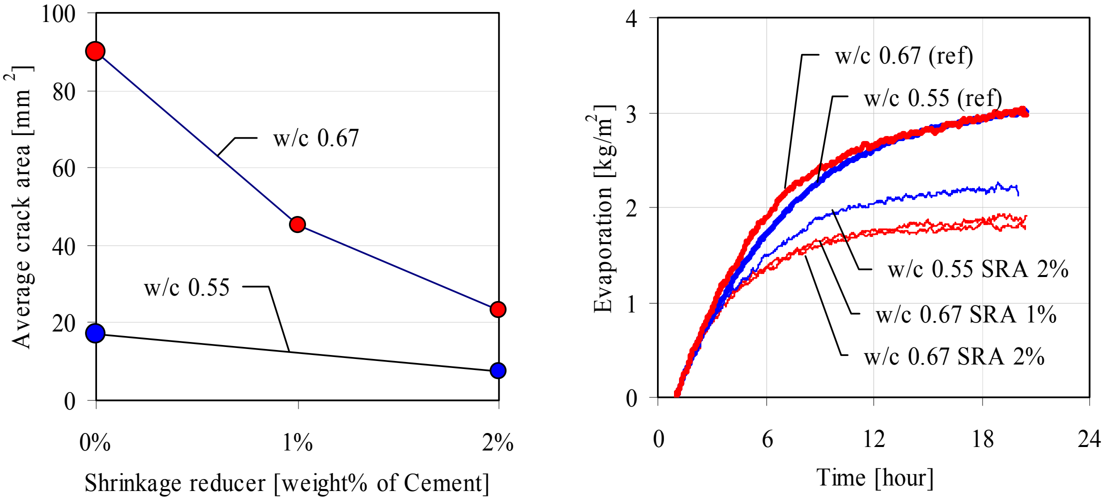
That the aggregates are important is well known, and it is beneficial to have large aggregates and a high aggregate content. The effect of the coarse aggregate content (8-16 in relation to total aggregate content) on crack area can be seen in Figure 12(a). As the coarse aggregate was reduced, the crack area increased. Interestingly, however, an increased amount of fine aggregate content also reduced the evaporation, as can be seen in Figure 12(b). This indicates that it is not only the evaporation which determines the cracking behaviour; also the autogenous deformation plays an important role.



(a) (b)

Figure 12: Influence of coarse aggregate content (8-16) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

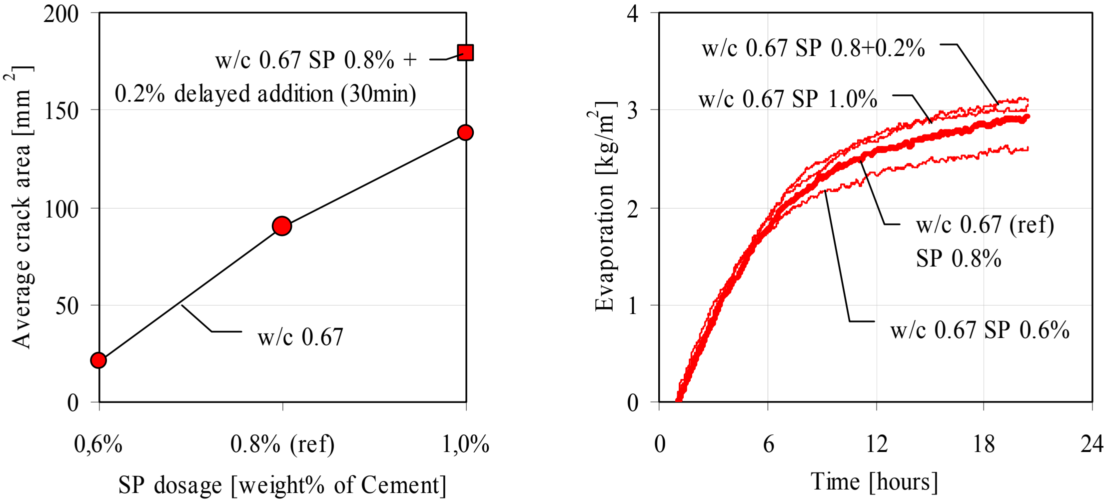
The shrinkage-reducing admixture (SRA) had a positive effect on the crack area. As can be seen in Figure 13(a), for both the investigated concretes (w/c 0.55 and 0.67) the crack area was reduced with SRA. The effect of SRA on the evaporation can be seen in Figure 13(b). This effect starts to be notable at about three hours, after which point the evaporation and its rate were significantly lower for the concretes containing SRA. The main effect of the SRA is that it reduces the surface tension of the water (or pore solution), which has a positive effect on shrinkage as it reduces the capillary tension caused by a reduction in pore radius. However, the SRA also influences the rate of drying; the concretes containing SRA had a significantly lower weight reduction than the reference concretes, and the mechanism is notable as soon as the hydration starts.



(a) (b)

Figure 13: Influence of shrinkage-reducing admixture (SRA) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

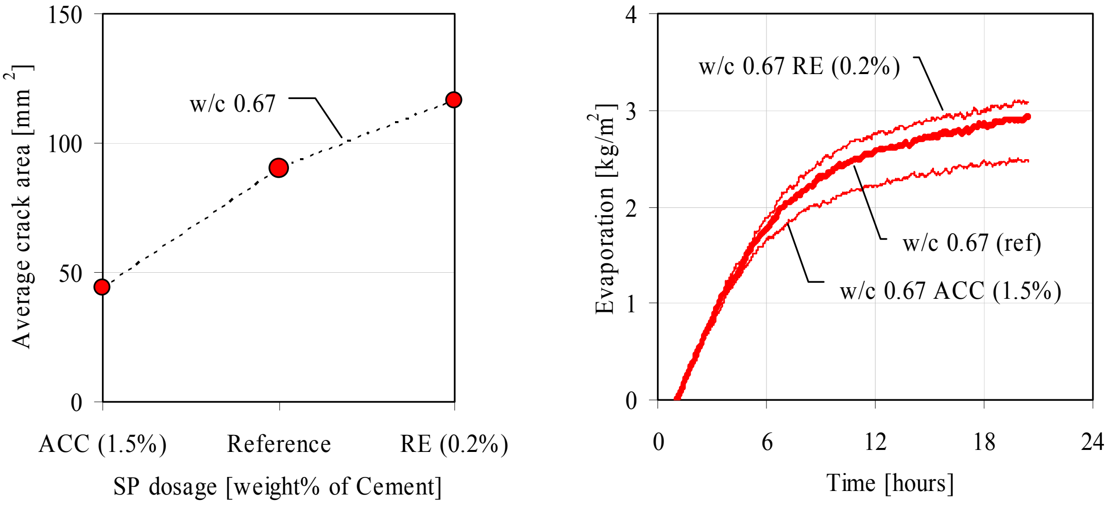
The superplasticizer dosage seemed to have a large influence on the average crack area. As can be seen in Figure 14(a), when the SP-dosage was reduced to 0.6% the crack area was significantly reduced, and with the high SP-dosage (1.0%) the crack area increased. For the case with a delayed additional SP-dosage (0.2% after 30 min) the crack area increased even more. The effect that the superplasticizer (SP) dosage had on the evaporation is presented in Figure 14(b). An increased dosage, as in the case with 1.0% and with a delayed dosage of 0.2%, resulted in an increased evaporation. With a reduced SP-dosage, 0.6%, the evaporation was reduced. That the evaporation increases is probably a result of the prolonged setting time.



(a) (b)

Figure 14: Influence of superplasticizer (SP) dosage on: (a) the crack susceptibility and (b) the evaporation (from [1]).

Similarly to the effect of the SP-dosage, accelerating and retarding the concrete had a considerable effect on the crack area, as can be seen in Figure 15(a). For the concrete with accelerator the crack area was reduced, while for the concrete with retarder the crack area increased. The effect that the accelerator and the retarder had on the evaporation can be seen in Figure 15(b), and is comparable to the effect that the SP-dosage had. For the concrete with accelerator the evaporation was reduced, and for the concrete with retarder the evaporation increased.



(a) (b)

Figure 15: Influence of accelerator (ACC) and retarder (RE) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

5. DISCUSSION

Based on the results of this study, the following paragraph contains a general discussion of the mechanisms leading to the formation of plastic shrinkage cracks, and a brief description of possible actions to counteract them is presented. The formation of plastic shrinkage cracks is governed by the development of capillary pore pressure. However, depending on the characteristics of the concrete, different mechanisms are responsible. For concrete with a high w/c-ratio, evaporation is the governing mechanism, while for concrete with a low w/c-ratio (or with the addition of silica) the autogenous deformation is the driving force. This is presented in Figure 16, which also indicates that the optimum concrete has a w/c-ratio of 0.55. These observations also suggest that, in order to avoid plastic shrinkage cracking, different actions need to be taken depending on the type of mechanism. A concrete with a high w/c needs to be protected against early evaporation (e.g. by a curing membrane: see [1]). For a concrete with a low w/c-ratio, protection against evaporation may not help, as experience shows (see [9]), and the autogenous deformation needs to be reduced. This can be achieved for example with a shrinkage-reducing admixture (which also reduces evaporation) or by an increased coarse aggregate content.

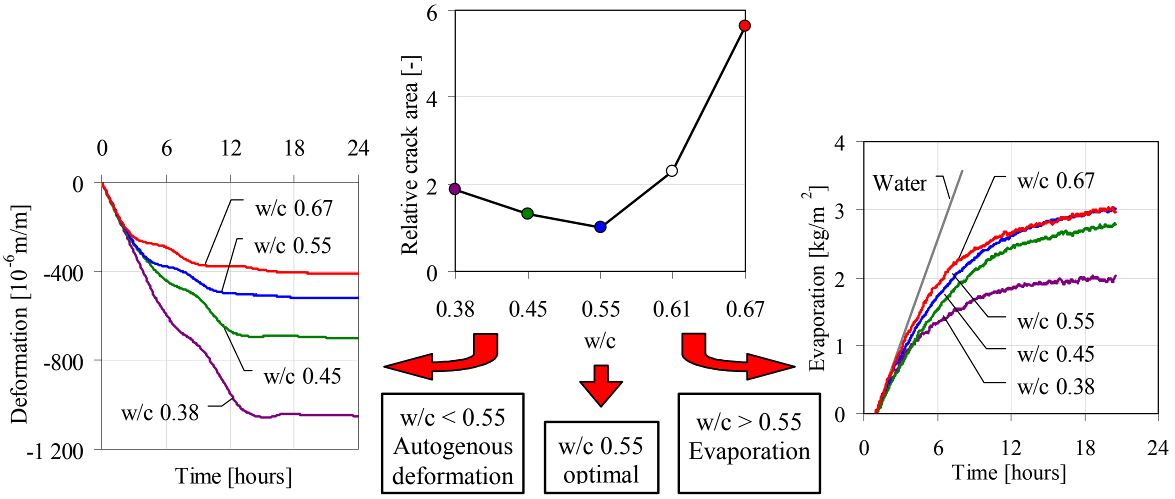


Figure 16: Separation of mechanisms governing the formation of plastic shrinkage cracks.

6. CONCLUSIONS

An experimental investigation of early age deformation and cracking tendency was made on a number of self-compacting concretes, having w/c-ratio between 0.38 and 0.67, and the influence of various mix parameters was investigated. Autogenous deformations were measured and the cracking tendencies were investigated in a restraint ring specimen.

The results from the measurements of linear autogenous deformation by the CDD show that:

- Increased cement content (lower w/c) increased the rate of and total chemical shrinkage and thereby the autogenous deformation.
- Increased coarse aggregate content decreased the magnitude and rate of autogenous deformation.
- Addition of silica fume increased the magnitude and rate of autogenous shrinkage and the effect increased with increased silica dosage. Silica fume decreased the time of the plastic period.
- Addition of shrinkage-reducing admixture (SRA) decreased the magnitude and rate of autogenous shrinkage for all concretes, and the effect increased with increased SRA dosage.
- Increased SP dosage increased the magnitude of autogenous shrinkage. SP dosage increased the rate of shrinkage at the plastic and semiplastic periods. After setting, the effect was the opposite, where the rate of shrinkage decreased with SP dosage.
- Accelerator (ACC) increased the magnitude and rate of shrinkage, and retarder (RE) had the opposite effect, in the plastic period (before initial setting). ACC and RE showed no significant effect on the time of the periods, but RE tended to delay the time to initial setting.

The conclusions that can be drawn from the restraint ring tests are that:

- The rate of evaporation was not always the governing factor for the cracking tendency.

- Silica fume led to increased autogenous deformation (the CDD experiments) and increased crack area in the ring test, though the evaporation was reduced.
- Reduced aggregate content increased autogenous deformation, while the evaporation was reduced.
- A shrinkage-reducing admixture (SRA) proved to be very effective in reducing the cracking tendency. SRA reduced the autogenous deformation as well as the evaporation.
- Delaying/retarding the hydration, with increased SP-dosage or by adding a retarder, increased both the autogenous deformation (the CDD experiments) and the crack area.
- Accelerating the hydration, e.g. by adding an accelerator, decreased both the autogenous deformation (the CDD experiments) and the crack area.
- The concrete with the high w/c-ratio (0.67) had the highest crack area. Furthermore, there seems to exist an optimum w/c-ratio for the investigated mixes, which indicates that the w/c-ratio should be in the region of 0.55; see Figure 10(a).
- The conventional concrete showed a similar tendency as the SCC (minimum cracking tendency at w/c 0.55) but, due to higher evaporation, it was found to be more susceptibile to cracking.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Esping, O. and Löfgren, I., 'Cracking due to plastic and autogenous shrinkage – Investigation of early age deformation of self-compacting concrete – Experimental study', Publication No 05:11, Department of Building Technology, Chalmers University of Technology, Göteborg 2005, 95 pp.

[2] Wittmann, F.H., 'On the Action of Capillary Pressure in Fresh Concrete', *Cement and Concrete Research*, Vol. 6 (1976), pp. 49–56.

[3] Gartner, E.M., Young, J.F., Damidot, D.A., and Jawed, I., 'Hydration of Portland cement'. Chapter 3 in *Structure and performance of cements* (ed. Bensted and Barnes), Spoon Press, London, 2002.

[4] Barcelo, L., Moranville, M., and Clavaud, B., 'Autogenous shrinkage of concrete: a balance between autogenous swelling and self-desiccation', *Cement and Concrete Research*, Vol. 35 (2005), pp. 177–183.

[5] Jensen O. M., Hansen F., 'A dilatometer for measuring autogenous deformation in hardening Portland cement paste', *Materials and Structures*, Vol. 28 (181), pp. 406-409, 1995.

[6] Johansen, R. and Dahl, P.A., 'Control of plastic shrinkage of cement'. Paper presented at the 18th Conference on Our World in Concrete and Structures, Singapore, 1993.

[7] NORDTEST NT BUILD 433, 'Concrete: Cracking Tendency – Exposure to Drying During the First 24 Hours'. NORDTEST (Espoo, Finland, 1995).

[8] Holt, E.E., 'Early age autogenous shrinkage of concrete'. Technical Research Centre of Finland, VTT Publication 446 (2001), Espoo, 184 pp.

[9] Bjøntegaard Ø., Hammer T.A., and Sellevold E.J., 'Cracking in High Performance Concrete before Setting', Proceedings of the Int. Symposium on High-Performance and Reactive Powder Concretes, Sherbrooke, Aug. 1998.