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EARLY AGE CRACKING OF SELF-COMPACTING CONCRETE

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Abstract

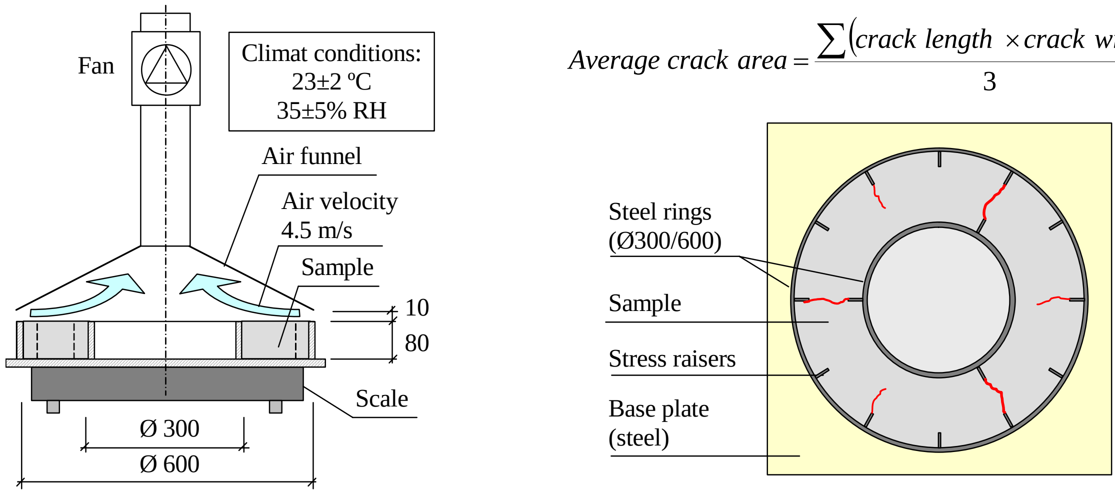
This paper deals with early-age cracking (< 24 h) due to plastic shrinkage which was evaluated using a restraint ring test. A large number of different SCC constituents and mix compositions have been investigated; e.g. w/c-ratio from 0.38 to 0.67, silica fume, and different admixtures. For comparison, tests with standard concrete were made. The influence of different constituents and mixes on the plastic shrinkage crack tendency was observed, and the results indicated that a high crack tendency was generated when the concrete had a large autogenous shrinkage (silica addition, low w/c) and/or high water evaporation (high w/c). Retardation (retarder, high superplasticizer dosage) also increased the cracking. The minimum crack tendency was found to be at w/c 0.55. Moreover, the crack tendency could be reduced by shrinkage-reducing admixture (large positive effect on both autogenous shrinkage and evaporation) or by acceleration. A wax membrane was effective for concretes with high evaporation. Finally, the ring-test method and the experimental results were also verified by field studies.

1. INTRODUCTION

Plastic shrinkage 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; see Esping and Löfgren [1]. 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.); see Bjøntegaard et al. [2]. 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 (see Kasai et al. [3]). There are two main driving forces for early-age shrinkage: (1) Early-age drying shrinkage may develop due to more evaporation than bleeding, and (2) shrinkage due to hydration and chemical reactions produces autogenous shrinkage. Temperature dilation may also in some cases contribute (e.g. when cooling the surface). When the concrete dries out due to evaporation, the loss of water from the paste generates negative capillary pressure, causing the paste to contract (see Wittmann [3]), 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.

2. PLASTIC SHRINKAGE CRACKING TEST METHOD

The method used is intended for determination of the cracking tendency of concrete at early ages, and was developed by Johansen and Dahl; see [5] and [6]. In the test, 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; see Figure 1. The test lasts for about 24 hours 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). In addition, the concrete temperature as well as the pore pressure development were recorded and the autogenous linear deformation was measured using a specially developed test method; see [1] and [7] and also [8].



$$Average\ crack\ area = \frac{\sum (crack\ length \times crack\ width)}{3}$$

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

3. LABORATORY EXPERIMENTS

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 litres, and 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: 30% and 40% (REF) 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 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. FIELD STUDY

In order to verify the laboratory results, a field study was undertaken in which the cracking tendency was evaluated on the ring-test specimens, and on larger slab elements that both were cast outside and exposed to the environment. The experimental setup used in the field study can be seen in Figure 2. The measurement of crack area was conducted in the same manner as for the ring-test specimens.

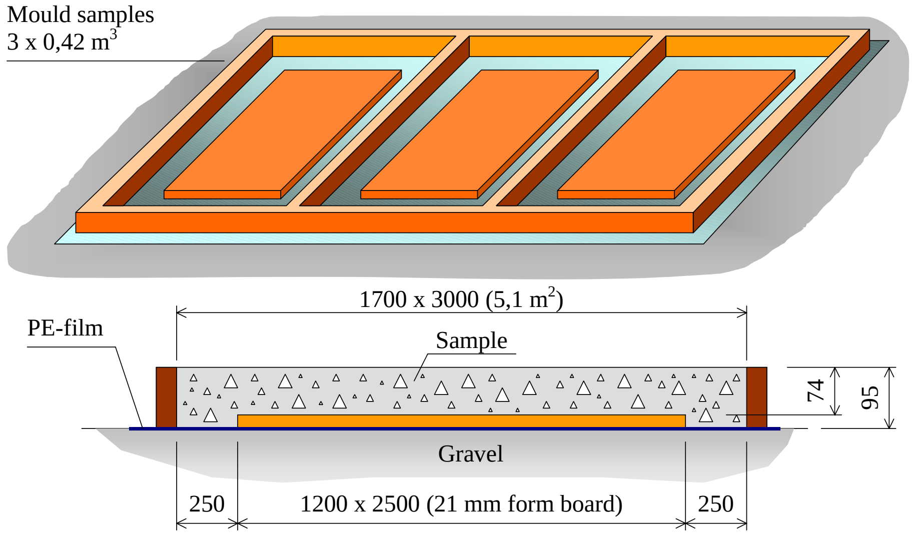


Figure 2: Experimental setup and geometry of the slab specimens used in the investigation.

The parameters investigated in the field study were:

1. The effect of a wax-based curing membrane (Antisol-E from SIKA, 0.2 l/m^2 applied) on reference concrete with w/c 0.67 – denoted 067 Antisol-E.
2. The effect of shrinkage-reducing admixture (dosage, 2% of cement content) in reference concrete with w/c 0.67 – denoted 067 SRA2.
3. The effect of additional SP-dosage (0.2% added in the truck) to reference concrete with w/c 0.67 – denoted 067 SP08+02.
4. The effect of fibres (0.1 vol-% polypropylene fibres) in reference concrete with w/c 0.67 – denoted 067 PP01.
5. The effect of adding extra water (12 litres added in the truck) to reference concrete with w/c 0.67 – denoted 067 W12.
6. The effect of w/c-ratio, comparing reference concretes 0.67 Ref and 0.55 Ref.

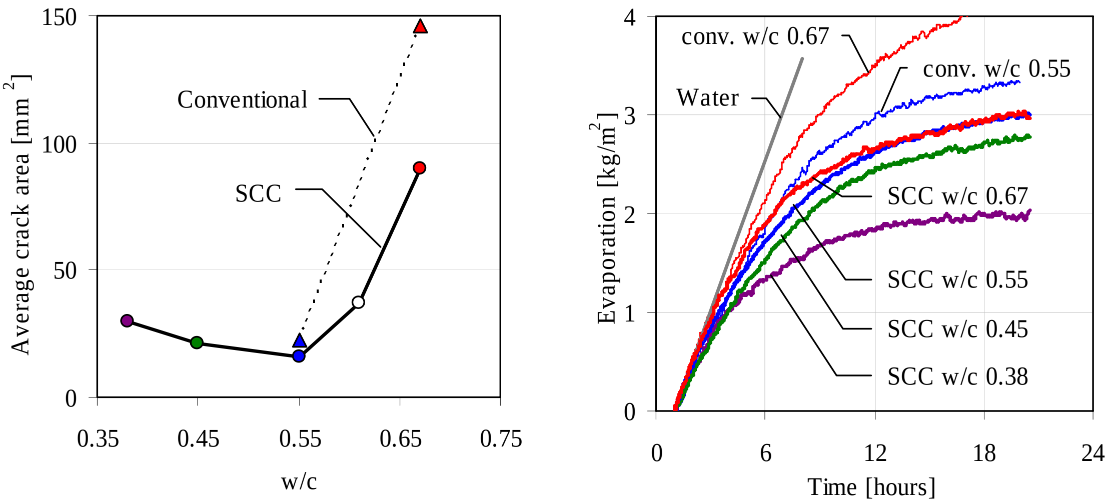
The field study was divided into three separate casting occasions, always with one slab and ring-test specimen made with the reference concrete with w/c 0.67, according to the following list:

I. Slab 1 with 067 SRA2, slab 2 with 067 Antisol-E, and slab 3 with 067 Ref.
II. Slab 1 with 067 PP01, slab 2 with 067 SP08+02, and slab 3 with 067 Ref.
III. Slab 1 with 055 Ref, slab 2 with 067 W12, and slab 3 with 067 Ref.

4. RESULTS

4.1 Laboratory experiments

The results for the average crack area for the reference concretes are presented in Figure 3(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 3(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 3: 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 4(a), increased dramatically. As can be seen in Figure 4(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; see Esping and Löfgren [1].

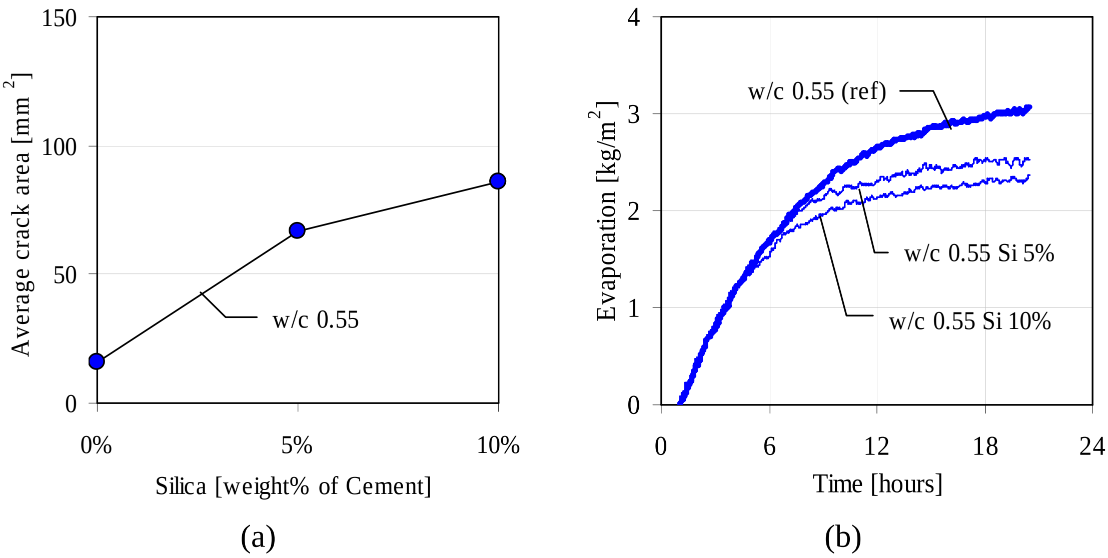


Figure 4: Influence of silica fume (Si) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

That the aggregates are important is well known, and it is usually 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 5(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 5(b). This indicates that it is not only the evaporation which determines the cracking behaviour; also the autogenous deformation plays an important role.

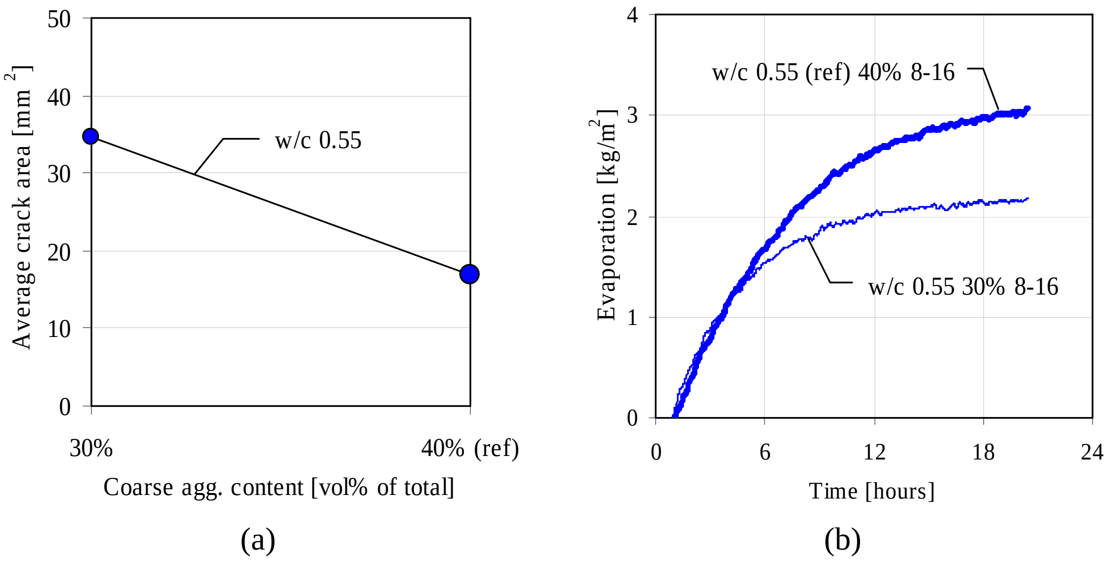


Figure 5: Influence of coarse aggregate content (8-16) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

The shrinkage-reducing admixture (SRA) had a considerable beneficial effect on the crack area. As can be seen in Figure 6(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 6(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; see [1]. 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.

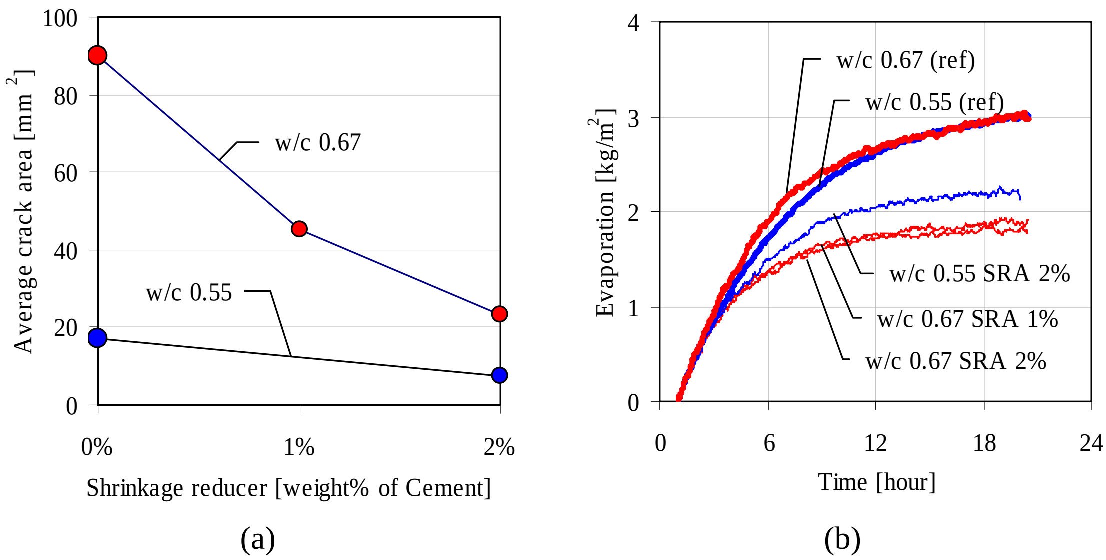


Figure 6: Influence of shrinkage-reducing admixture (SRA) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

The superplasticizer dosage seemed to have a large influence on the average crack area. As can be seen in Figure 7(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 7(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. 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 7(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 7(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.

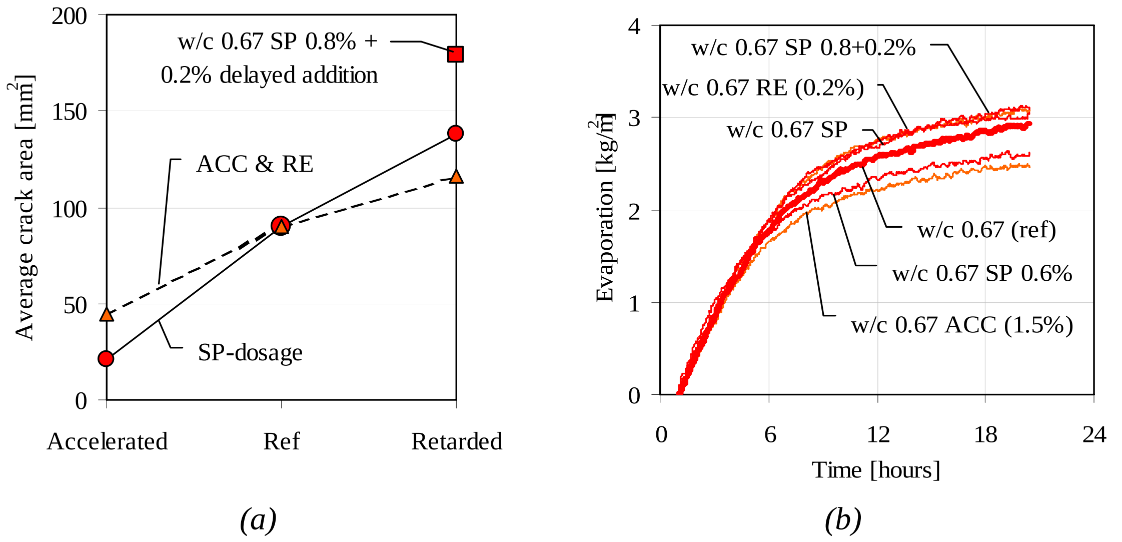


Figure 7: Influence of acceleration and retardation (SP-dosage or accelerator and retarder) on: (a) the crack susceptibility and (b) the evaporation (from [1]).

4.2 Field study

The weather conditions during the field study are shown in Figure 8, as average values for periods of six hours: wind speed in Figure 8(a), temperature in Figure 8(b), and relative humidity in Figure 8(c). The temperature was highest during field study II, which also had the lowest relative humidity and highest air velocity. During field study III the temperature and the air velocity were lower and the relative humidity was higher.

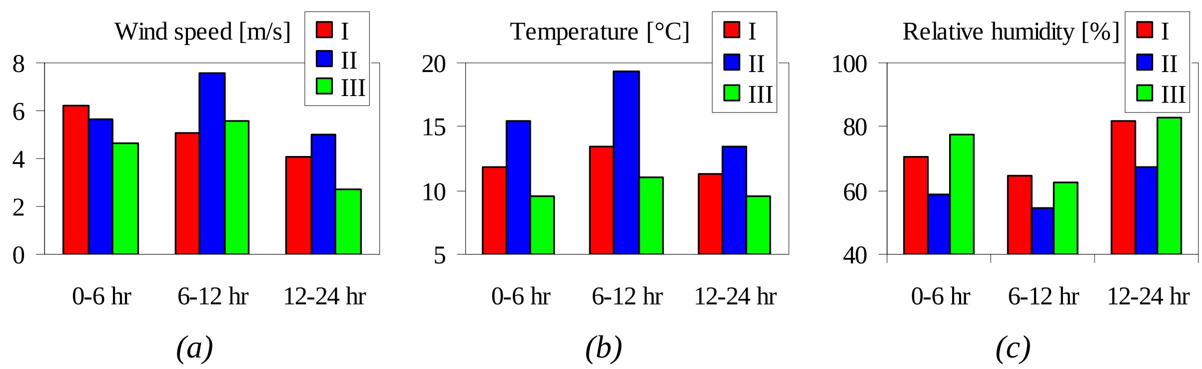


Figure 8: Weather data: (a) wind speed, (b) temperature, and (c) relative humidity.

For field study I, Figure 9(a), it can be seen that the shrinkage-reducing admixture (SRA) and the wax membrane (SIKA Antisol-E) significantly reduced the crack area, compared to the reference concrete. Moreover, the same trends can be observed for both slab and ring-test specimens. For field study II, Figure 9(b), it can be seen that the polypropylene fibres significantly reduced the crack area while the additional SP-dosage increased it. For field study III, Figure 10(a), it can be seen that the reference concrete with w/c 0.55 has a smaller crack area, compared to the reference with w/c 0.67. Furthermore, adding extra water increased the crack area. In addition, when comparing the reference concrete (067 Ref) which was present in all three field studies, Figure 10(b), it can be seen that when the weather conditions were favourable (filed study III) the crack area was significantly lower, approximately only one tenth in comparison to field studies I and II.

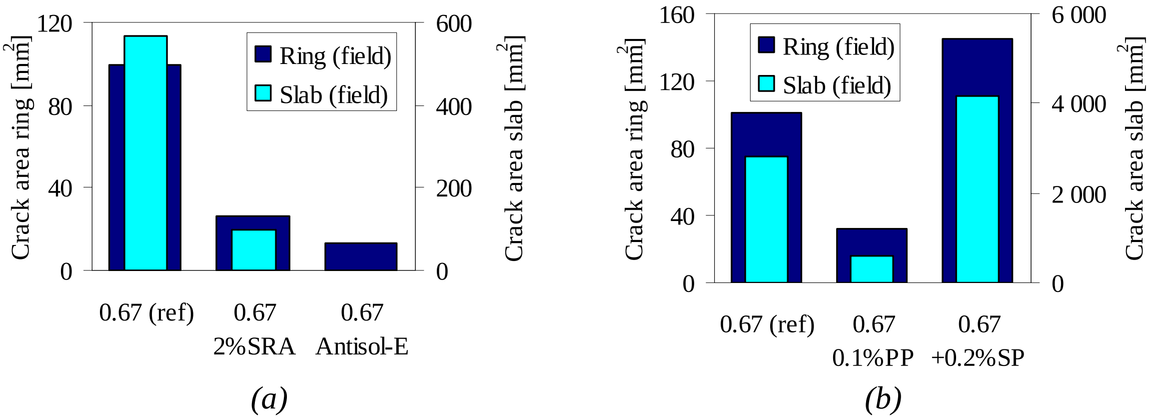


Figure 9: Comparison of crack area for field study I (a) and field study II (b).

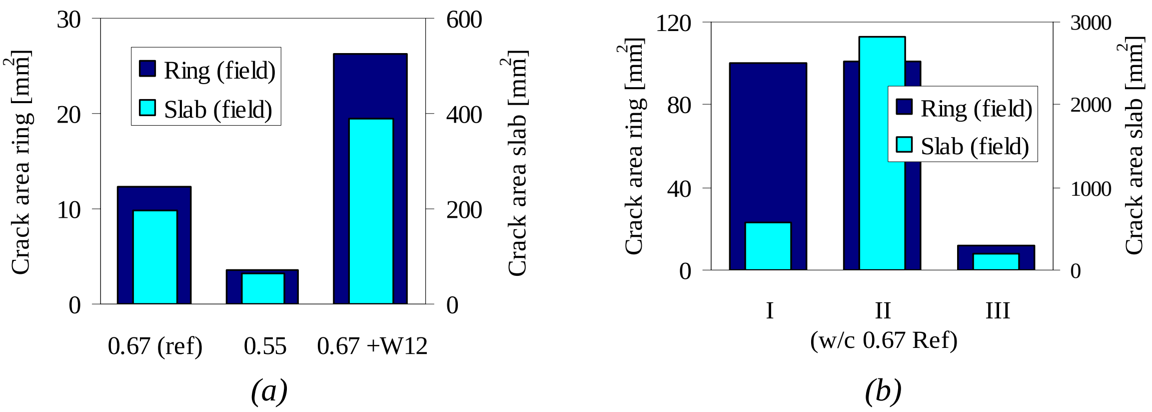


Figure 10: Comparison of crack area for field study III (a), and (b) comparison of crack area for the reference concrete (w/c 0.67 Ref) for the three occasions.

When comparing the results from the laboratory tests and the field study of a relative crack area (using 067 Ref as reference), and by calculating the Pearson correlation coefficient, it can be seen (Table 4) that the correlation is strong (close to one; a value >0.8 indicates a strong correlation) between the ring tests performed in the laboratory and the field study (both the ring test and the slab specimens). Furthermore, there is a high correlation between ring-test specimens of the filed study and the slab specimens.

Table 4: Correlation matrix between the ring tests performed in the lab and the ring-test and slab specimens used in the field study.

	Ring test lab	Ring test field	Slab test field
Ring test lab	1		
Ring test field	0.99	1	
Slab test field	0.98	0.99	1

5. 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. The cracking tendencies were investigated in a restraint ring specimen and, in addition, a field study was conducted, where slab and ring-test specimens were cast and placed in the field. A high correlation was found between the results of the ring tests performed in the laboratory and the field study, and between the ring-test specimens and the slab specimens.

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 crack area in the ring test, though 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 the crack area. Accelerating the hydration, e.g. by adding an accelerator, decreased 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 3(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 susceptible to cracking.

ACKNOWLEDGEMENTS

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