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Plastic Shrinkage Mechanism in Concrete Cracking

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Abstract
Plastic cracking is one of the major problems in concrete. During the summer, dry months of the year it is by no means scarce to find cracks appearing on the surface of the concrete within a little duration of its placement. Plastic cracking is very divergent from the cracks which come on account of thermal movement. They notice to roughly follow their straining element, eg. Changein the concrete section. An integrated appeal to the bridle of cracking processes and damage of concrete, including the kinetics of crack accretion depending on the time and the magnitude of the external load is proposed. After casting up to 24 hours cracking may become problematic in any concrete structure. It can destruction the aesthetics of the concrete member and decrease the durability and serviceability by facilitating the entrance of dangerous material. Plastic shrinkage cracking create most commonly in concrete with a large surface area such as in slab and floor. As the moisture is removed, the surface concrete decrement, resulting in tensile stresses in the weak material. To prevent cracks in concrete reduce water content & proper concrete mix design, curing, compaction etc.

Keywords: accretion, appeal, bridle, divergent, plastic shrinkage concrete, scarce, etc.

1.0 INTRODUCTION

Cracking of concrete reduces its barrier qualities and accelerates weathering attack, resulting corrosion of embedded reinforcing steel bars. Cracking of concrete also negatively affects the structural performance of the concrete-based infrastructure. The shrinkage of concrete when it is still in semi-fluid (plastic) state is referred to as plastic shrinkage [1]. Plastic shrinkage cracking generally occurs on the exposed concrete surfaces which, due to more rapid drying, undergo greater plastic shrinkage movements when compared with the body of concrete. Internal restraint of the surface plastic shrinkage can thus cause cracking of concrete surfaces between the time of placement and the final setting of concrete [2]. Exposure of concrete surfaces to windy, warm and dry conditions accelerates plastic shrinkage cracking.

Research on plastic shrinkage mechanism in concrete have generally concluded that capillary stresses near the exposed concrete surfaces which usually caused by the imbalance between the rates of bleeding and water evaporation, are the primary drivers of plastic shrinkage movements [3, 4]. Plastic settlements have also been found to influence plastic shrinkage of concrete [5]. The mechanisms of plastic shrinkage are mainly physical [4, 6]; whereas chemical phenomena have minimal effects on the early-age (plastic) shrinkage of concrete.

Control of plastic shrinkage cracking of concrete has been a subject of several investigations. Plastic shrinkage reducing admixtures have been used to lower the moisture evaporation rate, leading to lower settlement [7, 8], thereby reducing the buildup of capillary pressure.

The concrete potential for cracking due to plastic shrinkage was reduced by using either superabsorbent polymers [9] or cellulose-based stabilizers [10]. Fibrous materials such as fibrillated polypropylene fibers were also used to minimize the cracking resulted from plastic shrinkage [11, 12]. Precautions such as moistening concrete surfaces with water or curing agents [13], or by applying cover sheets to minimize evaporation during construction should be taken to prevent plastic shrinkage [14]. Cracking of concrete due to plastic shrinkage is still a major concern especially in areas of large exposed surfaces such as slabs on grade, repairs on thin surfaces, tunnel linings, patching, etc. [15, 16]. In such applications, the ratio of the concrete surface area to its total volume is relatively high, and the original concrete subgrade surface also works as a high degree restraint.

Efforts to develop new classes of hydraulic cements should address the concerns with plastic shrinkage cracking and the related material properties of concrete. In this work, concrete was prepared using a new cement chemistry (alkali activated cement) and tested for plastic shrinkage cracking.

The hydraulic cement used in this work relies on alkali activation of aluminosilicate for production of hardened binder. Alkali activated cements have been recently used as a sustainable replacement to Portland cement binder [17]. Alkali activated binders can be synthesized using several aluminosilicate precursors with different availability and reactivity levels (such as slag, coal fly ash, clay, volcanic tuffs, etc.) [18, 19]. The concrete material prepared using alkali activated binders have shown promising results regarding resistance to severe conditions such as acids and sulfates, fire and corrosion resistance [20, 21]. Even though alkali activated aluminosilicate binders have been used in many investigations, the plastic shrinkage and bleeding characteristics have not been studied yet.

The work reported herein investigated the plastic shrinkage cracking resistance of alkali activated cement concrete. The bleeding and rheological attributes of alkali activated cement pastes were also measured. Portland cement paste, and concrete were tested as control materials. The distinctions between the alkali activated and Portland cement were identified and explained based on the experimental results.

1.1 SCOPE OF WORK

Rapid evaporation from the surface of fresh concrete causes negative pressure, known as capillary pressure, in the pore system. This pressure pulls the solid particles together and decreases the inter-particle distances, causing the whole concrete element to shrink. If this contraction is hindered in any way, the induced tensile stresses may exceed the low tensile strength of the concrete, leading to cracking. The phenomenon, which occurs shortly after casting while the concrete is still in the plastic stage, is mainly observed in elements with high surface to volume ratio such as slabs and pavements. Many parameters may affect the probability of plastic shrinkage cracking. Among others, effect of water/cement ratio (w/c), fines, admixtures, geometry of the element, ambient conditions (i.e. temperature, relative humidity, wind velocity and solar radiation), etc. has been investigated previously. In the presented research, in addition to studying the influence of various parameters, i.e. w/c, cement type, coarse aggregate content, superplasticizer dosage, admixtures, and steel fibres, effort is made to reach a better and more comprehensive understanding about the cracking governing mechanism. Evaporation, capillary pressure evolution and hydration rate are particularly investigated in order to identify their relationship.

1.2 OBJECTIVES

- To obtain a reliable and meaningful method to measure the linear autogenous shrinkage of concrete.
- To study addresses the plastic shrinkage cracking phenomena and tests the use of the re-vibration of concrete after one and half hours from concrete placing to reduce the plastic shrinkage cracking.
- To investigate the time-dependent development of material properties including free shrinkage, modulus of elasticity in compression and split tensile strength tests for several bridge deck mix design.
- To compare the effects of different curing durations on the extent of shrinkage-induced cracking in bridge deck concrete.

2.0 MAIN FACTORS AFFECTING PLASTIC SHRINKAGE CRACKING

Fig. summarizes the process of plastic shrinkage cracking and the factors [38] which can affect the phenomenon. A deep comprehension on how these factors influence the whole cracking process can lead to invention of new crack preventative methods. Some of the factors are briefly. described in the following

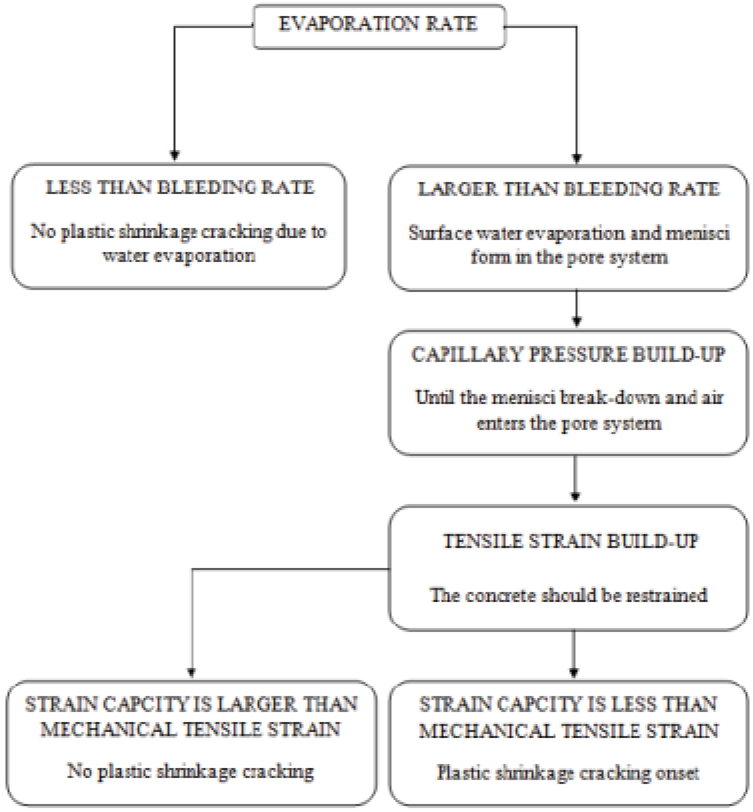


Figure Plastic shrinkage cracking flowchart

a. Water/Cement Ratio:

Water/cement ratio significantly affects the plastic shrinkage cracking tendency. Assuming constant mixture constituents, higher w/c ratio causes more bleeding water [28] and vice versa. In case of high w/c ratio, thus, it takes longer time for the surface water layer to disappear due to evaporation and consequently delays the capillary pressure build-up in the pore system. However, this is highly dependent on the concrete mix. A lower amount of cement in SCC with low w/c ratio often is compensated with more fines (e.g. filler) in order to avoid segregation [42] and reduction of durability and serviceability.

b. Additives:

Several studies have been carried out to find new admixtures in order to reduce the plastic shrinkage of concrete. These admixtures show high practicality in reducing evaporation rate [11], settlement, negative capillary pressure and plastic shrinkage formation [14]. For instance, it has been concluded that cellulose-based viscosity modifying agent (stabilizer) causes reduction of the evaporation rate in cementitious material. Accelerator (ACC) and retarders have a strong influence on the plastic shrinkage cracking tendency[31] .Some experiments showed that accelerator admixtures cause higher plastic shrinkage and total crack area, while retarders act contrary. On the other hand, super plasticizer (SP) reduces the need for water in the concrete mixtures i.e. less bleed water. This reduction of surface water may however not increase the risk of cracking.

c. Fibres:

Fibres (steel and/or polypropylene) often have been used in concrete mixtures [7] in order to reduce the width of the plastic shrinkage cracks, through stitching the concrete surface particles together. Experiments performed by Sivakumar and Santhanam show that a combination of steel and polypropylene fibres (hybrid fibres) [29], can reduce the width of the plastic shrinkage cracks up to 55%. However, despite of the lower crack width, parallel cracksmay form around the main crack [13]. This phenomenon can be due to the transfer of the shrinkage stresses, through the fibres, to the surrounding areas.

d. Fines Content:

Fines such as fly ash, silica fume, slag, etc. lead to a larger total specific surface area of the binder [13], and narrower pores. Consequently, the water that is supposed to be transported to the concrete surface will be trapped inside and adsorbed by the fine particles, resulting in lower bleeding rate compared to a concrete with lower volume of fines [27]. The higher surface area of the particles leads to higher tensile capillary pressure [7] and eventually higher probability of plastic shrinkage crack formation. Moreover, experiments showed that silica fume increases the crack tendency in the concrete, despite of the evaporation reduction. Accordingly, using high proportion of fine material in the concrete mixture is not favorable as regards to plastic shrinkage cracking.

e. Depth of the Concrete Section:

A deeper concrete member typically experiences more settlement. As a result, more water is being transported to the concrete surface trough the pore system leading to a larger water accumulation on the surface [19]. This means that the surface water layer evaporation takes longer time, causing delay in capillary pressure build-up.

f. Curing Measures:

Plastic shrinkage cracks can be avoided through several post-casting curing measures. These measures in general aim at reduction of the surface water evaporation[14]. For instance, sealing the concrete surface (e.g. covering the concrete with plastic sheet) decreases the evaporation rate and consequently can lead to a crack free concrete[23]. In another case, experiments have shown that evaporation of the surface water can be suppressed through spraying aliphatic alcohols over the fresh concrete surface[9]. Compensating the evaporated water (rewetting) is another way to protect the fresh concrete against plastic shrinkage cracking.

3.0 TEST METHODS AND MEASURING TECHNIQUES

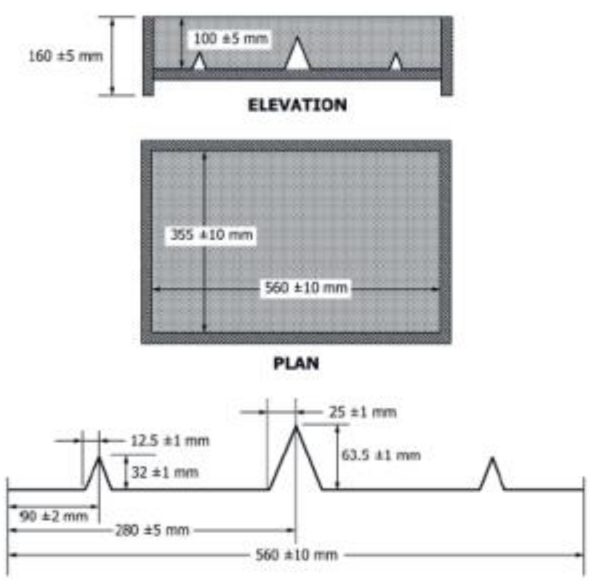
Restrained specimens

In this particular research, the impact of the tested parameters on cracking was investigated using two different test setups, i.e. ASTM C 1579 (ASTM, 2006), and ring test method, also known as NORDTEST-method NT BUILD[15] .

ASTM C1579

Nevertheless, its application is not limited to only fibre reinforced concrete (FRC) [33], and can be extended to include other parameters as well. This mould was used in Papers II and III, for studying the effect of admixtures and steel fibres on the cracking of plastic concrete[12]. The mould was made of stainless steel. The stress riser in the middle acted as a crack initiation point, while the other two smaller metal inserts on the sides internally restrained the specimen. The interior sidewalls [5] were coated with a thin layer of oil, in order to reduce the bond between the concrete and the mould. The experiments took place in a climate chamber to ensure constant ambient conditions (T = 20 ± 1˚C and RH = 30 ± 3%). A fan was located next to the mould to generate wind velocity of 8 ± 0.5 m/s across the concrete surface[18]. The cracking reduction ratio (CRR), which defines the percentage of reduction in the crack width in the FRC (ASTM, 2006), was calculated as follows:

$$CRR = \left[1 - \frac{Average\ \ crack\ \ width\ \ of\ \ FRC}{Average\ \ crack\ \ width\ \ of\ \ control\ \ concrete\ \ mixture}\right] \times 100$$



Geometry of the ASTM C 1579 mould, from (ASTM, 2006)

Ring test method (NT BUILD 433)

The ring test method (NORDTEST-method NT BUILD 433) [4] was first developed by Johansen and Dahl at NTNU, in order to determine the influence of mixture constituents on the cracking potential of fresh concrete at a "macro" level. This method was used in a series of experiments performed[14]. However, the ring test setup used in the current work deviates from that of Esping and Löfgren by the different capillary pressure measuring technique. The test setup consisted of three identical moulds[16], each having two concentric steel rings with 300 mm and 600 mm in diameter and 80 mm in depth, see Figure. The surface of the stainless steel baseplate[2] was coated by a thin layer of oil.

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

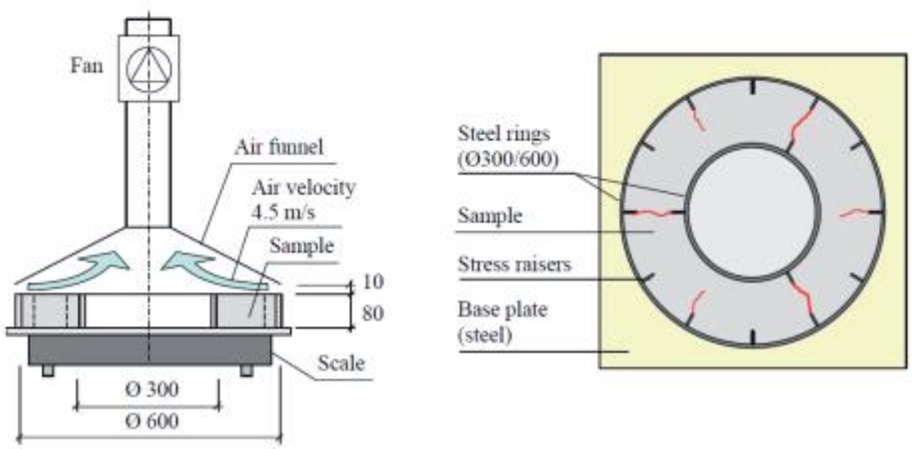


Figure Ring test setup for plastic shrinkage cracking tendency determination

Rectangular mould test setup

For the first several experiments performed in this work, a rectangular mould (1200×400×90 mm) [44] has been manufactured based on the experimental setups used. As mentioned before, the results are not reported in the appended papers. However, more information are presented . The mould was made of UPE80-beams[1] placed on a 1 mm thick stainless steel baseplate. Three rebars with 8 mm in diameter were used on each side to restrain the concrete slab. The rebars [26] were fixed against 18 bolts around the mould (6 bolts along the length and 3 bolts along the width of the mould). The bolts penetrated the concrete by 60 mm.

Figure Two rectangular mould test setups with fans and wind tunnels, placed on four load-cells

Evaporation
The mass loss of the specimens was considered equal to the amount of the evaporated water. Thus, as described before, the moulds were placed on 3 to 4 load-cells[43], i.e. scales, by which the weight reduction was recorded continually. The load-cells were connected to a computer, where the data (to an accuracy of 0.001 kg), was collected, illustrated, and analysed in a Catman data acquisition software (DAQ)[9], Produced by HBM.

Bleeding
The bleeding test was performed according to the method proposed [40]. A steel cylindrical vessel, 250 mm in both diameter and height, was filled with concrete, immediately after mixing. The vessel was covered by a plastic sheet to prevent water evaporation[29]. The water accumulated at the surface was collected with a pipette after 15, 30, 45 and 60 minutes. According to EN 480-4 [15], during the bleeding test, the specimen surface must be covered with a lid/plastic sheet to prevent surface water evaporation, which means that the ambient conditions are different from those under which the plastic shrinkage tests[29] take place.

Hydration heat
The internal temperature was recorded with a number of thermo threads[23], which were inserted into the concrete directly after casting. The thermo threads were connected to a computer via a data-logger (Spider 8)[30], where the readings were collected and analysed in an EasyView software[35], produce by Intab.

Capillary pressure
The capillary pressure was measured using Capillary Pressure Sensor System (CPSS), manufactured by Research and Transfer Centre (FTZ)[36] at the Leipzig University of Applied

Science (HTWK Leipzig)[41]. The cone of the sensor should be filled with degased water[11] and penetrate the concrete surface to a depth of around 4 - 5 cm.

4.0 EXPERIMENTAL RESULTS

This was clearly observed in the pressure measurements during the experiments, where at 4 cm from the concrete surface, the pressure developed with the identical rates, regardless of the sensors' position, see Figure. The relationship between the capillary pressure build-up rate and the tension inside the concrete mass[44], explained, may be comprehended from the results of the present research. For example, in Figure, by comparing the values of capillary pressure for SCCs with different w/c, it can be seen that the pore pressure, at 4 h after casting, is -38 kPa for REF (w/c=0.67), and around -27 kPa for the others. Thus, REF[17] presumably, experienced higher shrinkage than the other mixtures. This was also observed in the photos taken at the end of the experiments, where the cracks in the reference specimen were about 10 times wider than those in W/C45[42], see Figure. Accordingly, the results presented in this chapter are analysed mainly based on the correlation between pore pressure build-up rate and hydration evolution, i.e. internal temperature.

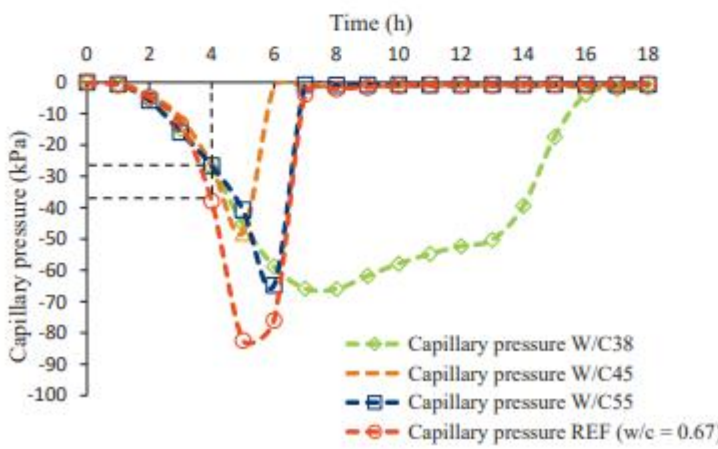


Figure Rete of capillary pressure build-up in SCCs with different w/c (0.38, 0.45, 0.55 and 0.67)

Effect of admixtures

The effect of retarder (based on phosphate), accelerator (based on calcium nitrate), stabilizer (based on organic polymer), air-entraining agent (based on synthetic surfactant), SRA (based on polymeric glycol), have been investigated in Paper II. The tested admixtures [16] were chosen due to their vast application in the Swedish construction sector. Table, presents the mix design of the tested concretes and the admixture content. The influence of the admixtures on cracking tendency [33] (i.e. crack area), evaporation, capillary pressure evolution, and the internal temperature development of the specimens are shown in Figure, respectively. The general properties of the mixtures, including slump flow, T500[18] (i.e. time for a 500 mm flow), bulk density and air content are presented in Table.

Table Mix design of the SCCs tested in order to study the effect of admixtures on plastic shrinkage, (REF = reference concrete, RET = retarder, ACC = accelerator, STB = stabilizer, AEA = air entraining)

Name	REF	RET	ACC	STB	AEA	SRA
Cement (kg/m3)	340	340	340	340	340	340
Water (kg/m3)	170	170	170	170	170	170
Agg. 0-4 (kg/m3)	785	785	785	785	785	785
Agg. 8-16 (kg/m3)	651	651	651	651	651	651
Filler (kg/m3)	160	160	160	160	160	160
SP (kg/m3)	4.08	4.08	4.08	4.08	4.08	4.08
Admixture (kg/m3)	-	6.5	7	3.74	6	10.2

Table General properties of the mixtures (REF = reference concrete, RET = retarder, ACC = accelerator, STB = stabilizer, AEA = air entraining agent and SRA = shrinkage reducing admixture)

Name	REF	RET	ACC	STB	AEA	SRA
Slump flow (mm)	760	650	730	410	720	800
T500 (sec)	2 3 x	2 3	2.5	-	2.5	2
Density (kg/m3)	2348	2357	2424	2392	2392	2392
Air content (%)	1.7	1.7	2.6	2.6	2.75	2.3

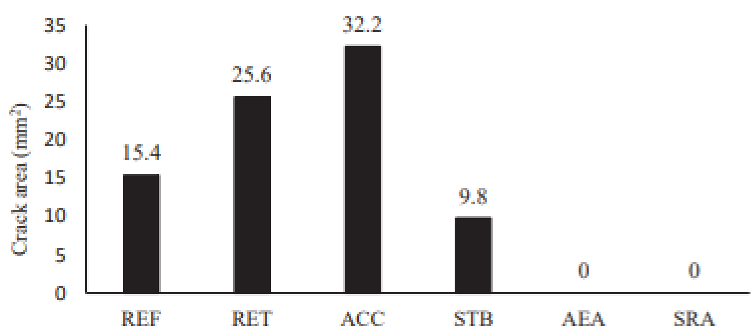


Figure Effect of admixtures on the average crack area of the tested specimens, measured at 18 hours after casting

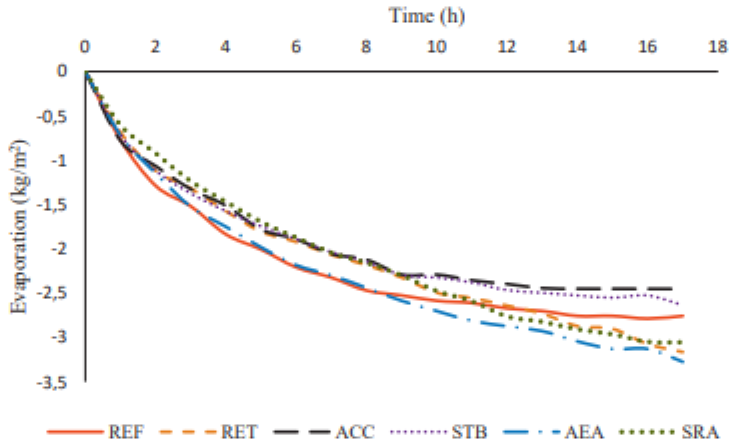


Figure Effect of admixtures on the evaporation

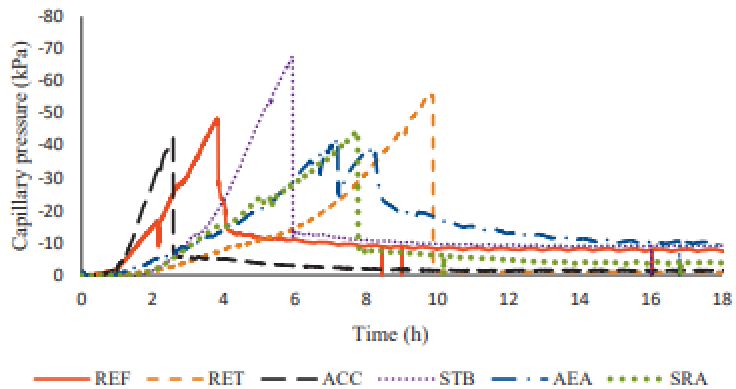


Figure Effect of admixtures on the capillary pressure evolution

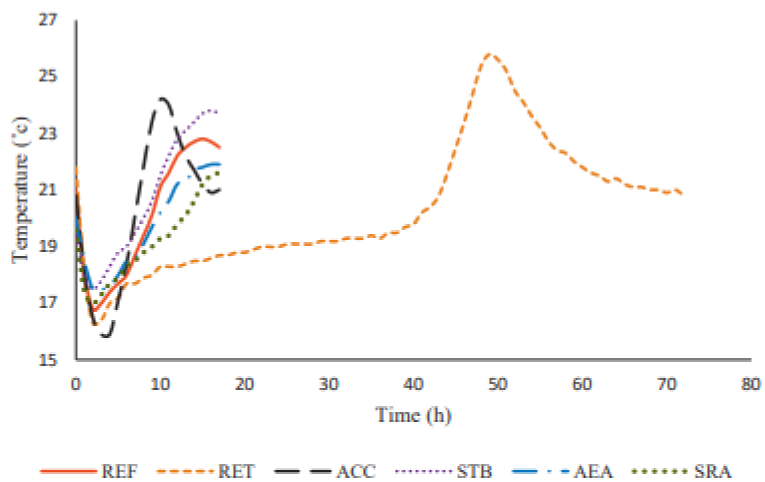


Figure Effect of admixtures on the internal temperature development of the tested specimens

The settlements of the specimens are plotted against their horizontal deformations [22] in Figure. It seems that in case of the cracked specimens, the pure gravity induced vertical deformation[37] increases as the horizontal shrinkage gradually decreases.

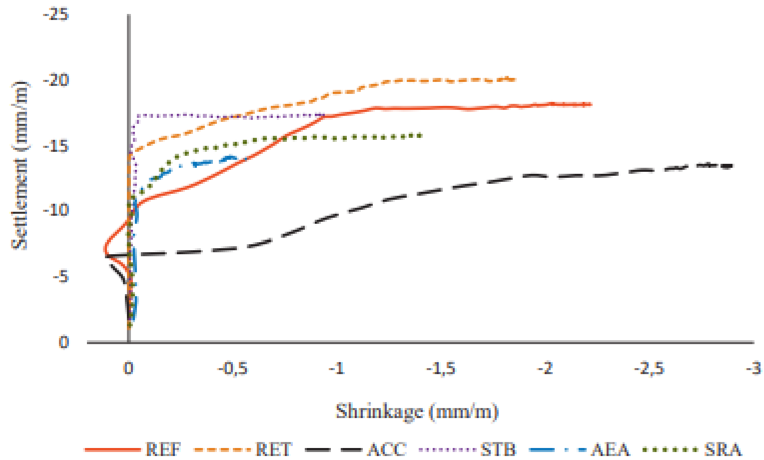


Figure Settlement vs. horizontal shrinkage of the concretes tested in the admixture experiments

Concretes with lower or higher w/c showed more tendency to early-age cracking, see Figure. However, cracking in concretes with w/c lower than 0.45 may be attributed to autogenous shrinkage[41], while plastic shrinkage is the main driving force behind the cracking[1], when w/c is higher than 0.55. This finding was also manifested in the variation of the crack initiation time, measured during the tests[5], where decreasing the w/c delayed the cracking.

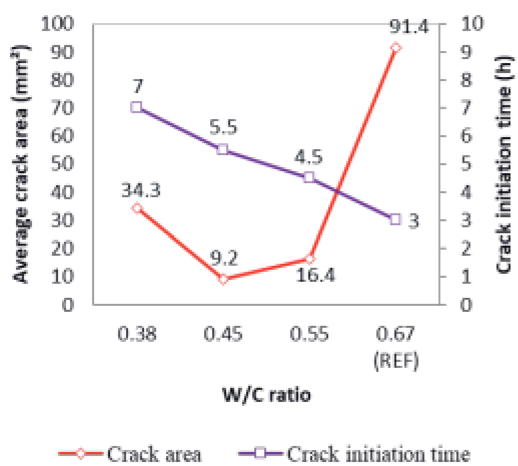


Figure Average crack area (measured at 18 h after casing and calculated), and time of crack initiation of SCCs in ring test setup with 0.38, 0.45, 0.55 and 0.67 w/c

Among the concretes, in which the w/c was changed, the largest crack area was measured in the one with 0.65 w/c, which had the highest capillary pressure build-up rate[12], see Figure.

Nevertheless, a reduction of the crack area was observed when the w/c was decreased. Although this reduction was not as significant as the one observed in the laboratory tests, see Figure, it still confirms the optimum range[5][17] of w/c (between 0.45 and 0.55), for mitigating the cracking severity. The difference, however, may be attributed to the different type of used cement, as a CEM II/A-LL 42.5R cement (Byggcement) was used in the laboratory experiments[29], while a CEM I 42.5N Cement (Anläggningscement) was utilized in the half-scale tests. Reducing the w/c, also decreased the capillary pressure rate, see Figure.

5.0 CONCLUSION

Plastic shrinkage is the phenomenon that may change under certain conditions & circumstances of the concrete. The area of any cracks increases with increase in rate of evaporation of surface water of concrete for any water cement ratio. Greater the cement to aggregate ration more the crack area & maximum crack width. Depending on the ambient atmospheric conditions crack width is also decide. The addition of low volume fractions of short flax fibres to Portland cement mortar specimens was found to be effective in reducing the cracking that results from restrained plastic shrinkage under conditions that produce high evaporation rates. Addition of fibres can effectively control the plastic shrinkage cracks of the concrete. If we replace the sand with pre wetted LWA can provide a significant reduction in settlement and plastic shrinkage cracking of mortars and concretes.. If a sufficient volume of pre wetted LWA is provided, plastic shrinkage cracking can be reduced or eliminated under the exposure conditions. Cracks in SCC produced by rapid hydrating cements are mainly autogenously, while those produced by slow hydrating cements are mainly subjected to plastic shrinkage cracking. A shrinkage reducing admixture and a paraffin-based curing compound were effective in preventing cracking. Based on the observed evaporation, settlement, capillary pressure and cracking behavior, the mechanisms for crack prevention were identified. As plastic shrinkage cracking is dependent on evaporation rate, settlement and capillary pressure, the concrete mix design, the duration of the dormant period, and the environmental conditions (concrete and air temperature, relative humidity and wind speed) ultimately determine the risk of cracking.

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