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ABSTRACT: Plastic Shrinkage Cracking (PSC) is one of the earliest forms of cracking in concrete and normally occurs within the first few hours after the concrete has been cast. Concrete elements with large exposed surfaces placed in environmental conditions with high evaporation rates are especially vulnerable to PSC.

The surface cracks that form are unsightly and serve as pathways, through which corroding agents can penetrate the concrete, ultimately lowering the overall performance of the structure. Although various precautionary methods exist, these are often neglected or ineffective due to the complex number of factors, which influence PSC and the general lack of supervision.

This paper investigates and describes the behaviour and nature of typical PSC in conventional and low volume polymeric fibre reinforced concrete that has been subjected to conditions with high evaporation rates.

The results indicated that the critical period for PSC formation is between the initial and final setting of concrete. Furthermore, concrete mixes with high bleeding and mixes, containing a low volume of polymeric fibres were shown to reduce PSC. This work is part of an ongoing research project that aims to create a performance-based guideline for the design of concrete elements to prevent/reduce PSC.

1. INTRODUCTION

Plastic Shrinkage Cracking (PSC) is mainly a problem for structural elements with large surface areas, for example bridge decks and floor slabs, which are exposed to environmental conditions with high evaporation rates. Such conditions are common in South Africa and are typically characterised by a low relative humidity, high wind speed and high temperature. The shrinkage or volume change of the concrete, which essentially causes cracking, is mainly due to the loss of free water from within the concrete through evaporation. The ongoing evaporation of water from the concrete surface causes water menisci to form between the particles, which tend to pull the particles together in both the horizontal and vertical direction. Due to an ever-present restraint, the capillary pressure becomes negative. This negative capillary pressure build-up is known to be the main mechanism that causes PSC [1, 2].

At a certain time, the radius of the meniscus between the particles becomes too small to bridge the gap between the particles and air then enters the concrete paste. This time of air entry is the event that initialises cracking and is the only time at which it occurs [2]. Furthermore, the shrinkage will only result in cracking if the concrete is restrained, otherwise free shrinkage would occur. Since concrete restraint is almost unavoidable in practice through the presence of underlying concrete, reinforcing steel, formwork and sub-grade concrete, cracking is required to facilitate the shrinkage or volume change of the concrete [3].

Although capillary pressure, air entry and restraint are required for PSC, there are also several other interdependent factors that influence PSC, for example: evaporation; bleeding; material constituents; setting times; and construction practices [4]. Of the mentioned factors; bleeding probably has the most direct influence on PSC. Bleeding is caused by the settlement of solid particles in the concrete paste due to gravitational forces. As the particles settle they displace water to the surface of the concrete, which compensates for surface drying of the concrete, thus inhibiting the capillary pressure build-up.

Proper construction practices such as curing and temporary windbreaks can in most cases prevent PSC, especially since PSC occurs in a relatively short time period. Another method which has been shown to reduce PSC is adding a low volume of polymeric synthetic fibres to concrete [5, 6]. This is known as low volume fibre reinforced concrete (LV-FRC) which refers to conventional concrete, and contains less than 0.2 % fibres as percentage of the total volume. If PSC occurs, the fibres will bridge the cracks and reduce further crack widening.

The methods mentioned above are often not utilised, or ineffective, due to a lack of knowledge and experience. If PSC is not prevented it may result in serious aesthetical and durability issues in concrete structures. From an aesthetic point of view PSC results in unsightly surface cracks in the concrete, which give a non-uniform appearance. In some cases these cracks can penetrate the full-depth of the concrete slab. More importantly, PSC results in durability issues due to the possibility of corroding agents infiltrating the concrete through the cracks.

This accelerates corrosion of any reinforcing steel, and concrete deterioration that consequently causes a reduction in the performance, serviceability and durability of the concrete structure [6, 7]. Furthermore, cracks formed during the plastic stage of the concrete may be further widened during the long-term drying of the hardened concrete structure, which again results in durability issues [8].

It is evident that PSC can and should be prevented. This paper aims to provide the fundamental understanding of PSC required to facilitate its prevention. It describes the nature and behaviour of typical PSC, with emphasis on the time period where it is most likely to occur. It also investigates the influence of adding a low volume of polymeric fibres to concrete on PSC. The investigation is based on several tests of concrete mixes in harsh environmental conditions inducive to PSC. The experimental results presented include measurement of the capillary pressure, evaporation, bleeding, setting times and crack growth all as a function of time.

2. TEST SETUP

The experiments were conducted in a climate chamber, which can create stable environmental conditions conducive to the formation of PSC. The chamber electronically controls temperature and relative humidity to preset values with a heating element and a dehumidifier respectively, while a variable airflow is created with two axial fans. The climate chamber can reach temperatures of up to 50 °C, relative humidities as low as 10 % and uniform wind speeds of up to 70 km/h.

Figure 1 shows the test compartment of the climate chamber where various moulds are placed for testing. The square moulds are continuously weighed with electronic scales to determine concrete water evaporation.

Figure 1 also shows the rectangular moulds used for PSC measurements as proposed by ASTM C 1579 [9], which were designed to give a single plastic shrinkage crack above the centre insert. The crack area was measured using high resolution images analysed with CAD software as shown in Figure 2

A Vicat needle apparatus was used to determine the initial and final setting times of the concrete in accordance with SANS 50196-3 [10]. As this test is designed for determining the setting time of cement paste, the fresh concrete was sieved through a 4.75 mm sieve to produce a mortar suitable for penetration resistance testing as proposed by ASTM C 403 [11]. The bleeding measurement method is similar to the method used by Josserand & De Larrard [12]. Two cylindrical PVC moulds were filled with concrete after which tracks were created on the concrete surface for bleeding water in which to accumulate. This water is extracted with a syringe and weighed with an electronic scale. The depths of the concrete in the bleeding, evaporation and cracking moulds were 100 mm.

3. TEST PROGRAMME

The standard concrete mix chosen for the experiments was based on mixes used by local ready-mix companies for

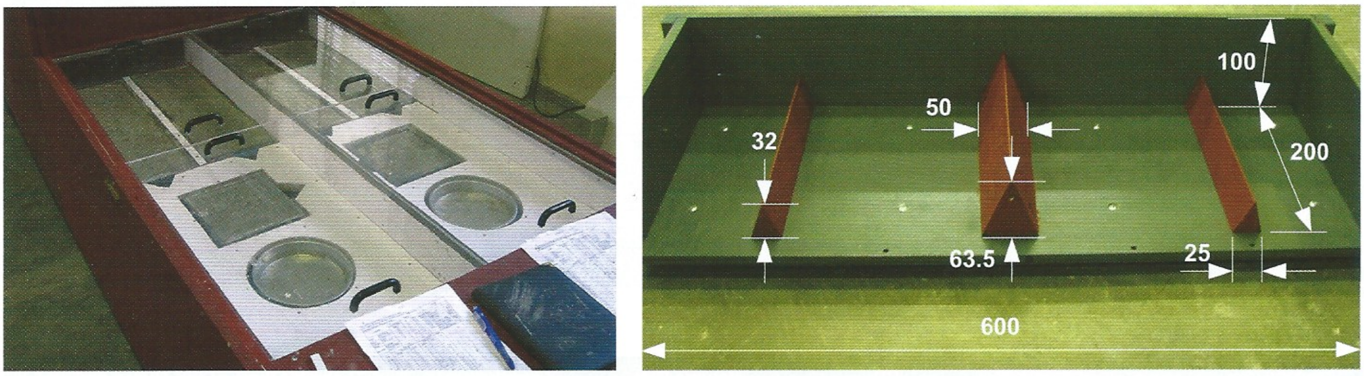

Figure 1: The test compartment of the climate chamber and mould used for crack measurements

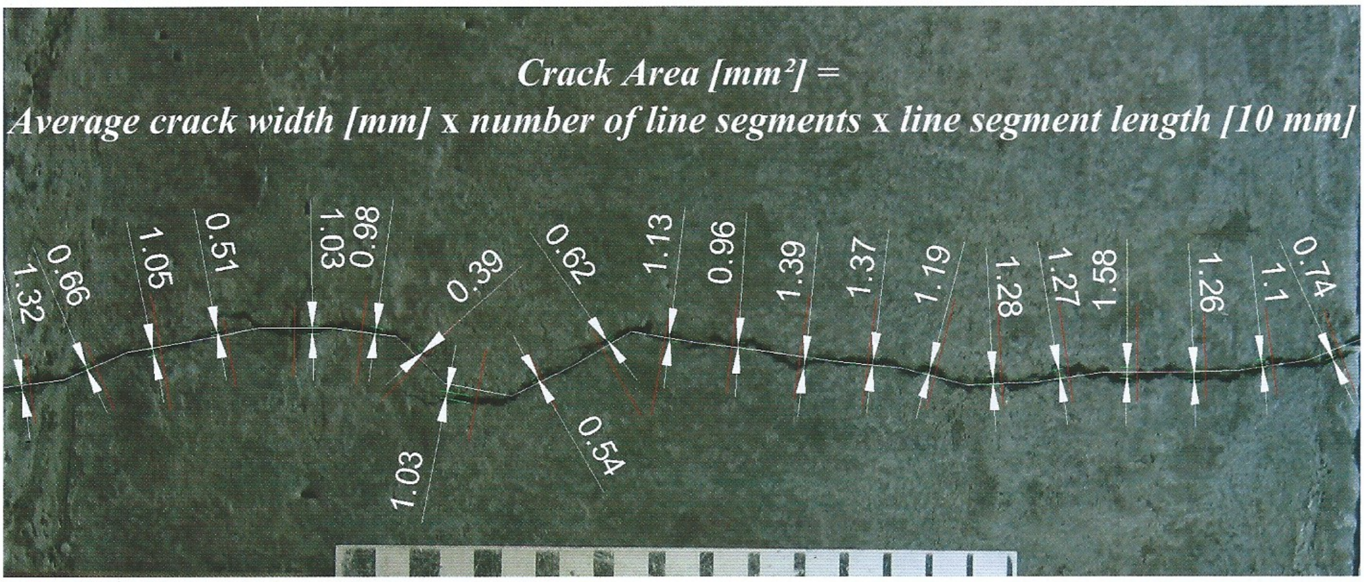

Figure 2: Example of crack area measurement and calculation

Capillary pressure measurement was based on the method used by Slowik [2]. Small electronic pressure sensors were connected to the pore system of each concrete specimen by long metal tubes, which were inserted horizontally 35 mm beneath the surface of the concrete. The tips of the tubes were located at the centre triangular insert of the moulds used for crack measurement which is also the expected cracking position.

industrial floor slabs. Three variations of the standard mix in terms of setting time and bleeding characteristics were also used. The setting times were varied by using a set accelerator and set retarder, whereas the bleeding was increased by using coarse natural sand. Tests were also done by using three different monofilament synthetic fibre types at a dosage for PSC reduction of 0.9 kg/m³ of concrete [5].

None of the mixes segregated had adequate workability for compaction with a poker vibrator. The 28-day compression strength of all the mixes was more than 25 MPa. Table 1: summarises the mix label, definition and description. Table 2: summarises the fibre properties and Table 3: shows the mix proportions and material constituents of all the mixes. With the exception of the bleeding, all the measurements were conducted in the climate chamber at an extreme environmental condition defined as Climate 1. The bleeding was measured outside the climate chamber at a less severe environmental condition defined as Climate 2. This was necessary to improve the accuracy of the measurement method. Table 4 shows a summary of the environmental conditions. Bleeding measurements were taken every 20 minutes until the final setting time was reached. The time 'zero' is defined as the time when the moulds were placed in the climate chamber, which was about 20 minutes after water was added to the mix. Two crack measuring samples were cast for every mix.

4. RESULTS

Figures 3 to 6 show the results of all the mixes that had visible cracks. Only the first sample of each mix is presented for simplicity and it should be noted that there were no significant differences between the results of the samples of each set.

The figures show the cumulative amount of bleeding and evaporation as well as the time of crack onset, time of crack stabilisation, initial and final setting times of concrete, capillary pressure build-up and the crack area as measured at specific times.

The time of plastic crack onset is defined as the time when the first crack is observed, and the time of crack stabilisation is defined as the time when a clear decrease in the rate of crack growth can be observed. The results of the mixes containing fibres are not presented since they showed no visible cracking

Table 1: Label, definition and description of mixes

Label	Definition	Description
MS	Mix Standard	Used for industrial floor slabs
MR	Mix Retarded	Retarded setting times
MA	Mix Accelerated	Accelerated setting times
MB	Mix Bleeding	Increased bleeding
MPES	Mix Polyester	MS with polyester fibres
MPP	Mix Polypropylene	MS with polypropylene fibres
MFPP	Mix Fluorinated Polypropylene	MS with fluorinated polypropylene fibres

Table 2: Fibre properties

Fibre type	RD	Volume [%]	Length [mm]	Diameter [µm]	Hydro-philicity
Polyester (PES)	1.38	0.07	12	18	Hydrophilic
Polypropylene (PP)	0.91	0.10	12	30-40	Hydrophobic
Fluorinated polypropylene (FPP)	0.91	0.10	12	30-40	Hydrophobic

Table 3: Mix proportions and material constituents

Mix name	MS	MA	MR	MB	MPES	MPP	MFPP
Content	[kg/m³]						
Fine natural sand (FM = 1.5)	503	503	503	-	503	503	503
Greywacke crusher dust (FM = 3.6)	506	506	506	506	506	506	506
Coarse natural sand (FM = 2.3)	-	-	-	486	-	-	-
19 mm Greywacke stone	950	950	950	950	950	950	950
OPC Cement [CEM I - 42.5N] (Surface area = 280 m²/kg)	270	270	270	270	270	270	270
Water	190	190	190	190	190	190	190
W/C ratio	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Plasticiser	1	1	1	-	1	1	1
Accelerator	-	1.51	-	-	-	-	-
Retarder	-	-	1.7	-	-	-	-
Polyester fibres	-	-	-	-	0.9	-	-
Polypropylene fibres	-	-	-	-	-	0.9	-
Fluorinated polypropylene fibres	-	-	-	-	-	-	0.9

Table 4: Environmental conditions

Condition	Relative humidity	Air temperature	Wind speed	Concrete temperature
Climate 1	20 %	40 °C	33 km/h	23 °C
Climate 2	55 %	23 °C	0 km/h	23 °C

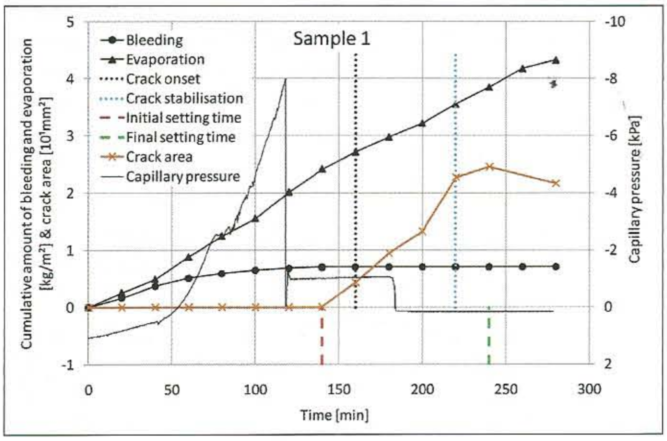

Figure 3: Result of MS (Mix Standard) at Climate 1

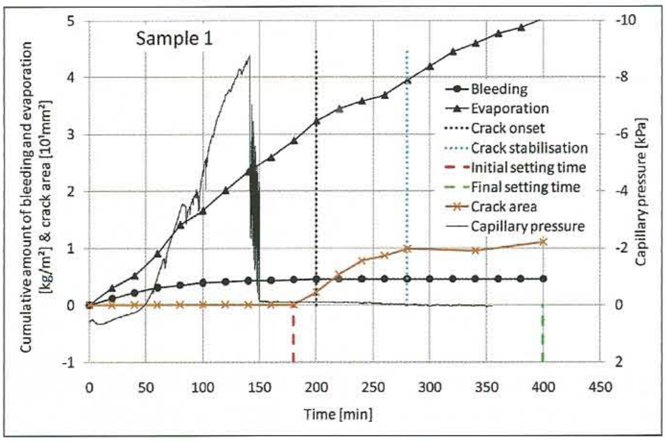

Figure 4: Result of MR (Mix Retarded) at Climate 1

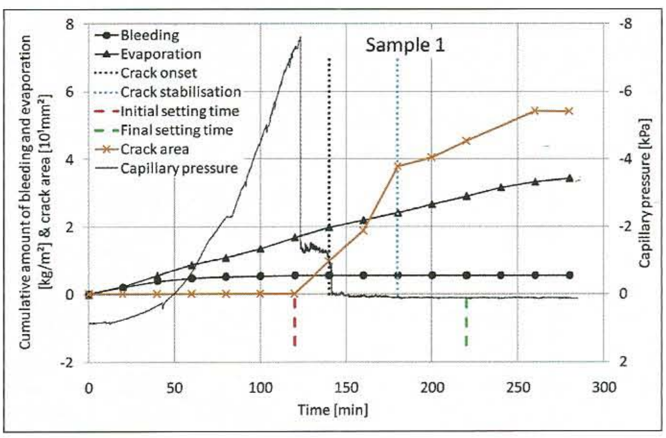

Figure 5: Result of MA (Mix Accelerated) at Climate 1

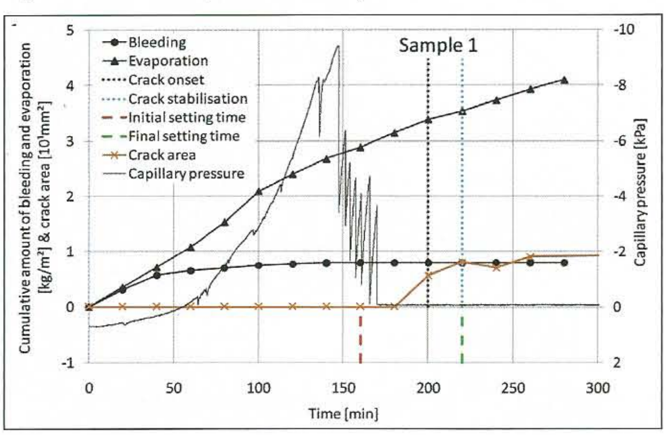

Figure 6: Result of MB (Mix Bleeding) at Climate 1

5. DISCUSSION

5.1 Nature of PSC

Figures 3 to 6 show the general behaviour of typical PSC. Once all the bleeding water on the concrete surface has evaporated the capillary pressure starts building up. This is the drying time, which occurs around 50 minutes after the concrete has been cast for all tests. After the drying time has been reached the negative capillary pressure increases significantly until air entry pressure is reached near the initial setting time of the concrete. Air entry can be recognised by a sudden drop in the capillary pressure. The first cracks are observed just after the initial setting time has been reached. This is called the time of crack onset which notably does not coincide with the time of air entry as would be expected. This is because at the time of air entry the crack has not yet widened, but only exists as a potential void between the concrete particles filled with air and not water [2]. As evaporation and therefore shrinkage continue, the crack widens and only becomes visible to the naked eye (time of crack onset) several minutes after air entry has occurred. The crack increases rapidly within a relatively short period of time and stabilises before the final setting time is reached.

5.2 Critical time period for PSC

Figure 7 summarises the important times for both samples of all the test sets including the tests containing fibres. It should be noted that MA only shows one data point for the time of air entry, since the capillary pressure measurement for the other sample malfunctioned.

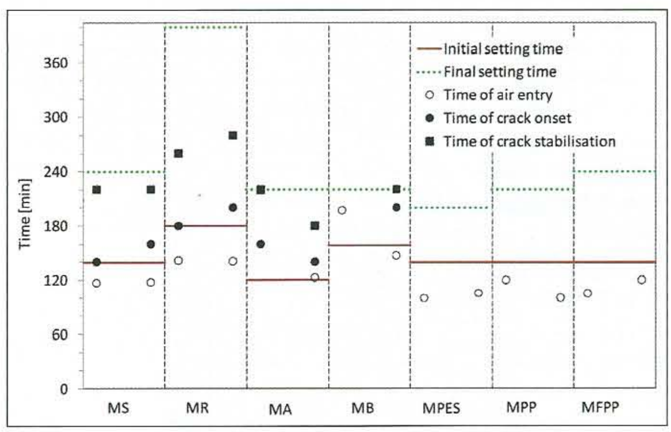

Figure 7 : Summary of important times for both samples of all mixes

The results indicate that cracking starts close to the initial setting time of concrete. Furthermore, there exists a close relationship between the initial setting time, time of crack onset and the time of air entry. This relationship sheds light on the reasons why cracking starts close to the initial setting time. Firstly, no cracking is possible before air entry has occurred [2], since air entry initialises any possible cracks. Secondly, the time of air entry also coincides with the time of maximum vertical settlement [2] which gives the point in time from where the majority of the shrinkage will occur in the horizontal direction. This horizontal shrinkage facilitates the formation of cracks and can be expected to start close to the initial setting time of concrete. However, this does not suggest that the initial set of concrete causes PSC and only indicates that conditions are favourable for the start of PSC at the initial setting time of concrete.

The results also give valuable information on when PSC ends. No new cracks started after the final set of concrete had been reached and crack stabilisation always occurred before the final setting time of the concrete. Nearly 80 % of the crack area at 40 minutes past the final setting time has already been formed by the time of crack stabilisation. Furthermore, per definition the rate of the crack growth after the time of crack stabilisation is insignificant if compared with the rate of the crack growth before the time of crack stabilisation as shown in Figures 3 to 6. The crack growth after the time of crack stabilisation may include cracks due to other types of shrinkage, for example thermal gradient and drying shrinkage. This makes it difficult to distinguish between the types of cracks that form after the time of crack stabilisation. However, based on this work it can be concluded that only PSC occurs before crack stabilisation given there is no differential settlement. Furthermore, the final setting time of concrete serves as a good indication of when PSC ends as the time of crack stabilisation typically corresponds with the final setting time.

The critical period where the majority of the plastic shrinkage cracks start and end is therefore between the initial and final setting times of concrete. Any preventative measure would be most effective if applied during this period.

5.3 Importance of bleeding

Figure 8 shows the cumulative amount of bleeding and the average crack area of both samples for each mix without fibres. The figure indicates that only once the bleeding rate becomes insignificant the cracking starts. It is however important to note that these tests were done in extreme environmental conditions.

The results support the observation that PSC starts close to the initial set of concrete, which in turn is closely related to the time of maximum vertical settlement. Since bleeding is caused by settlement, it would be reasonable to assume that the time of maximum vertical settlement will also coincide with the time when bleeding becomes insignificant. The results confirm this assumption and emphasises the influence of bleeding on PSC.

The results also indicate that MB with the most bleeding showed the smallest crack area and MA with much less bleeding showed the largest crack area. It is clear that bleeding has a significant influence on PSC. In general, the more concrete bleeds, the less the severity of PSC. However, it should be noted that too much bleeding may lead to surface laitance, which results in a concrete surface with poor quality and strength as well as bleed channels and voids under aggregate particles and reinforcing steel [4].

It is often argued that concrete with a delayed setting time is more prone to PSC [13, 14]. The results of MR, that is the concrete containing a retarder, showed the opposite, i.e. less PSC. Also, the MA samples, containing an accelerator, showed an increase in PSC. One possible reason for this is that concrete with a delayed setting will relieve the capillary pressure build up, even though there is a high rate of evaporation. Once the initial set occurs, after which point the PSC can begin, the water available to evaporate is less compared to concrete that sets earlier. The opposite is true for concrete with an accelerated setting time. In this case, once the initial set occurs, more water is available for evaporation, thus increasing the severity of PSC. This, however, requires further investigation; especially since Krönlof et al. [15] has shown that the addition of admixtures often has an unexplainable effect on PSC behaviour.

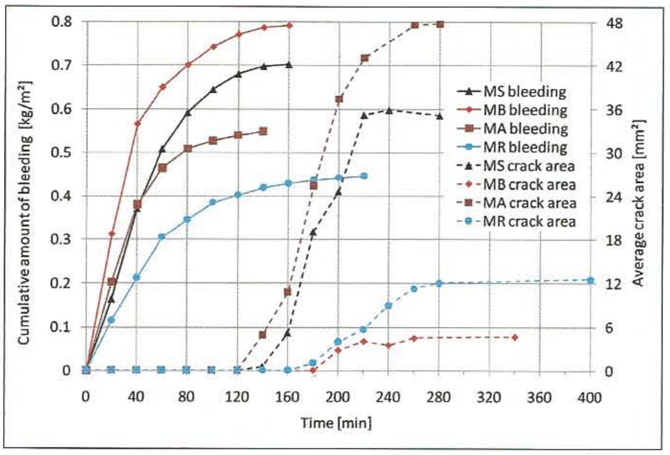

Figure 8: Graph of cumulative amount of bleeding and average crack area for mixes without fibres

5.4 Pre-cracking influence of fibres on PSC

Although fibres only start reducing crack growth once the crack has been formed, it still influences the bleeding and capillary pressure which directly influences PSC. The addition of fibres to MS reduced the bleeding significantly as shown in Figure 9.

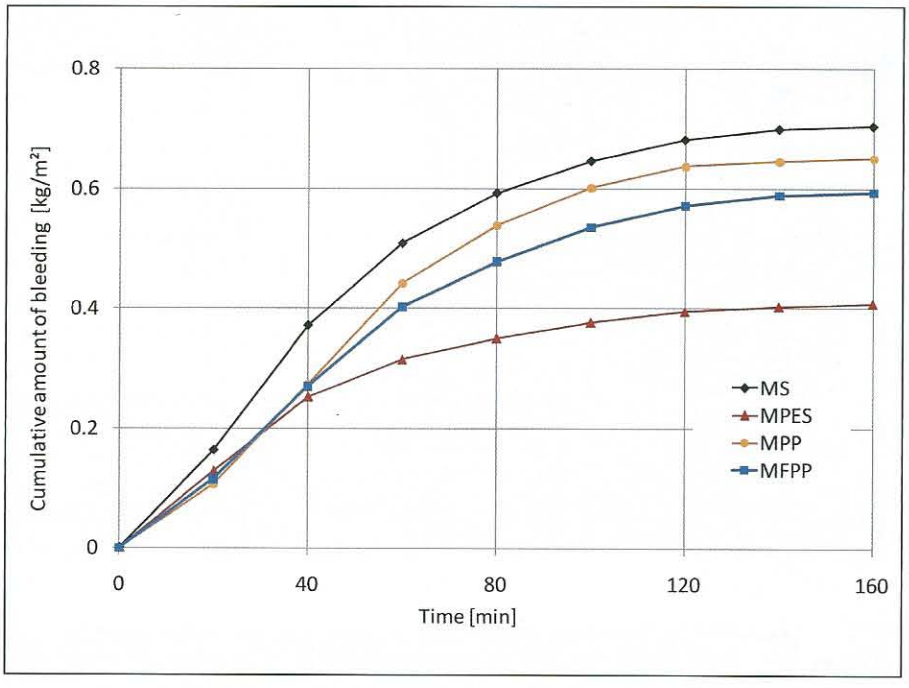

Figure 9: Effect of fibres on bleeding

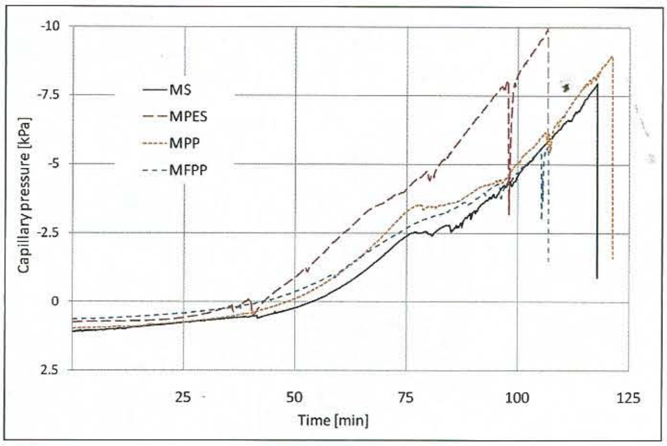

Figure 10: Effect of fibres on capillary pressure

This reduction is due to the fibres which reduce the settlement and therefore the bleeding [16]. The addition of polyester fibres resulted in the largest bleeding reduction, due to its hydrophilic nature which allows the fibre to absorb water. It should be mentioned that in certain cases fibres may increase the bleeding rate of a concrete mix, by acting as channels whereby water can move to the surface [16]. Depending on the effect of the fibres on the bleeding, the capillary pressure will also be influenced. The addition of fibres reduced the bleeding in the tests reported in this paper, and therefore explains the increase of the rate of negative capillary pressure build up as shown in Figure 10. An increase in negative capillary pressure also increases the risk for PSC which to an extent counteracts the reduced risk of PSC due to the addition of fibres.

6. CONCLUSIONS

The following conclusions regarding PSC in conventional concrete and low volume polymeric fibre reinforced concrete can be drawn: PSC does not occur before the initial set of concrete and PSC stabilises around the final setting time. This period is identified as the critical period for PSC

Bleeding has a strong influence on PSC where an increase of bleeding will reduce PSC.

The addition of polymeric synthetic micro fibres can reduce or even eliminate PSC. The addition of a low volume of polymeric micro fibres to concrete typically reduces bleeding. However, the PSC is still reduced as a result of the fibre addition even though the bleeding is reduced.

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