INFLUENCE OF RESTRAINT ON THE EARLY AGE CRACKING OF CONCRETE WITH AND WITHOUT FIBRES

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Summary: The restraint of freshly cast concrete is ever present through factors such as reinforcing steel and non-uniform concrete depth. The influence of these restraints on the early age cracking of concrete such as plastic settlement cracking (PSeC) and plastic shrinkage cracking (PShC) is of great importance, since these cracks are both unsightly and can cause severe durability and maintenance issues early in the life of a concrete structure. PSeC is caused by the differential vertical settlement of a concrete mix, whereas PShC is caused by the horizontal contraction of the concrete mix due to evaporation. The exact influence of these two types of cracking on each other is still unclear. However, since the same settlement/bleeding and restraint influence both cracking types, it is imperative to determine how these cracks influence each other. With this in mind, this paper investigated the influence of a specific restraining condition on both PSeC and PShC as well as the interaction between the two cracking types. The restraining condition promoted both PSeC and PShC. The results indicated that under extreme environmental conditions with high evaporation rates, PSeC can force the early and unexpected development of the majority of cracking mainly due to the combined effect of PSeC and PShC. For normal environmental conditions with low evaporation rates, PSeC can occur without any capillary pressure build up or air entry. The results also showed a significant increase in the vertical settlement due to capillary pressure build up. Finally, the addition of a low volume (0.6 kg/m\textsuperscript{3}) of polypropylene fibres seemed to have no influence on the PSeC or the interaction between PSeC and PShC at extreme environmental conditions.

1 INTRODUCTION

The problems associated with the early age cracking of concrete is well known and includes being unsightly and resulting in severe durability issues, all of which may lead to premature maintenance or even structural failure [1, 2]. The concrete elements most vulnerable to early age cracking are also known and include most concrete elements with large exposed surfaces, for example building slabs and bridge decks. Finally, most of the important influencing factors are also known, for example: conditions with high evaporation rates, mixes containing a high fine content and poorly executed or neglected curing practices [3]. However, although the problems, problem elements and influencing factors are known the exact cause or causes remains, at this stage, unclear and requires further investigation and clarification. With this in mind, this study aimed at investigating one of the often neglected but still crucial factors that influences the early age cracking of concrete, namely restraint.

The restraint of freshly cast concrete is almost unavoidable. Even in unreinforced concrete elements with a uniform depth, restraint is present through a combination of the shape and surface
roughness of the formwork or sub-grade and the differential drying of the concrete element. The latter is caused by the loss of moisture of the exposed concrete surface due to surface water evaporation compared to the inner, unexposed part of the concrete, which then restrains the shrinkage of the drying top concrete. Any shrinkage that is restrained causes stresses and finally cracking if the induced stresses are higher than the capacity of the material [4].

Both the induced stresses and the material capacity of fresh concrete are extremely low if compared with normal stresses induced in hardened concrete. This has made the measurement and prediction of these stresses problematic. One of the most recent and probably most comprehensive attempts made to determine the tensile capacity of early age concrete was done by Doa et al. [5]. However, Doa et al. did not determine the tensile capacity of concrete younger than 1.5 hours. The practical use of such information for the prevention of early age concrete cracking therefore remains questionable, because not only does early age cracking often occur before 1.5 hours after casting the concrete but also since both the induced stresses and material capacity will be different for each environmental condition, time after casting and mix proportions. Even if this information could be determined for any circumstances, it still does not consider the possibly significant influence of restraint on the early age cracking of concrete.

The presence of restraint in freshly cast concrete such as reinforcing steel, non-uniform concrete depth and underlying concrete have already been highlighted. However, the exact influence of these restraints on the early age cracking of concrete is still unclear. First of all, there are two types of early age cracking to consider, plastic settlement cracking (PSeC) and plastic shrinkage cracking (PShC). PSeC is caused by the differential vertical settlement of the concrete due to rigid inclusions such as reinforcing steel [6], whereas PShC is caused by the horizontal contraction of the concrete due to the capillary pressure build up [7, 8]. The capillary pressure is caused by the formation of water menisci between the solid particles of the concrete paste due to the evaporation of water from the concrete surface. Bleeding water reduces the capillary pressure build up to a certain extent and is caused by the settlement of solid particles in the concrete which displaces water to the concrete surface. Furthermore, at a certain point in the capillary pressure build up process, the radius of the menisci between the solid particles becomes too small to bridge the gap between them and cause air to enter the concrete paste. This is called the air entry pressure and is considered a requirement before any PShC can occur [8].

The same restraint in concrete is therefore essential for the occurrence of both types of cracking, where PSeC requires vertical- and PShC horizontal restraint. Furthermore, restraint also fundamentally influences one of the most critical processes involved with PShC, namely bleeding. It can therefore be concluded that to fully understand the influence of restraint on the early age cracking of concrete it is also necessary to understand the interaction between PSeC and PShC. This paper provides insight into the influence of restraint on both types of cracking as well as the interaction between the two cracking types. This was achieved by conducting several experiments on ordinary concrete as well as low volume fibre reinforced concrete (LV-FRC) mixes with a newly developed test setup that aims to isolate both cracking types by implementing certain boundary conditions. The influence of fibres on PSeC is of special interest, since it has already been shown that fibres reduce PShC [3, 4]. During these tests all the important influencing factors such as bleeding, evaporation, capillary pressure, crack growth, settlement, setting times and environmental conditions were continuously monitored.

2 EXPERIMENTAL FRAMEWORK

A specific mould was designed to promote both PSeC and PShC in fresh concrete using certain boundary or restraining conditions. The mould is shown in Figure 1 and is made of PVC and Perspex plastic panels which are supported by a steel platform. The Perspex side panels are transparent which allows the measurement of settlement. The mould is 400 mm in length and 200 mm in width. Furthermore, the mould varies in depth along its length and consists of a shallow section with a depth of 50 mm and length of 300 mm as well as a deep section with a depth of 200 mm and length of 100
The crack is forced at the position of depth variation which results in the differential settlement or restraint required for PSeC. There are also two triangular inserts or restraints in the mould. The bigger triangle is situated at the variation in depth and assists in creating two clearly defined settlement zones. The smaller triangle is placed near the end of the shallow part of the mould and provides the horizontal restraint required for PShC. The ratios of the triangles are identical to moulds used for fresh concrete testing as proposed by ASTM C 1579 [9].

Two ordinary concrete mixes, one with high and the other with low bleeding or settlement characteristics, were chosen for the experiments. The high bleeding mix (HB-Mix) used a coarse natural sand and low cement content, all of which reduced the fine content that increased the permeability and therefore also the bleeding of the concrete mix. On the other hand, the low bleeding mix (LB-Mix) achieved a low permeability and therefore low bleeding by containing a high cement content and by adding a mechanically crushed Greywacke dust sieved through a 2 mm sieve. Table 1 shows the proportions and material constituents of both mixes. A low volume of polypropylene fibres was also added to both mixes at a dosage of 0.6 kg/m³ of concrete. The mixes containing fibres are called the HBF-Mix (high bleeding mix with fibres) and LBF-Mix (low bleeding mix with fibres) respectively. The fibres have a length of 12 mm and a thickness of between 30 and 40 μm. In total four different mixes were used for experiments and all these mixes showed good workability with no segregation.
Table 1 : Mix proportions and material constituents

<table>
<thead>
<tr>
<th>Content</th>
<th>High bleeding mix (HB-Mix)</th>
<th>Low bleeding mix (LB-Mix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (CEM II - 32.5 N)</td>
<td>370</td>
<td>510</td>
</tr>
<tr>
<td>Water</td>
<td>205</td>
<td>250</td>
</tr>
<tr>
<td>13 mm Greywacke stone</td>
<td>900</td>
<td>800</td>
</tr>
<tr>
<td>Coarse natural sand</td>
<td>920</td>
<td>385</td>
</tr>
<tr>
<td>Greywacke crusher dust (sieved 2 mm)</td>
<td>0</td>
<td>400</td>
</tr>
</tbody>
</table>

The moulds containing the mentioned mixes were placed in an electronically controlled environmental chamber designed to create a stable hot, dry and windy environmental condition by using a heating element and dehumidifier as well as two axial fans [10]. Figure 2 shows the environmental chamber on the left and the test compartment of the chamber containing all the moulds is shown on the right. The chamber was used to create both an extreme environmental condition called Climate E and a normal environmental condition called Climate N. Climate E had an air temperature \((T_a)\) of 40 °C, relative humidity \((r)\) of 20 % and wind speed \((V)\) of 33 km/h whereas Climate N had an air temperature of 23 °C, relative humidity of 55 % and wind speed of 2.2 km/h. The initial placement temperature \((T_c)\) of all the concrete mixes was controlled at 23 °C for both climates. Both climates are common to South Africa and Climate E resulted in a high evaporation rate of more than 1 kg/m²/h and Climate N resulted in a low evaporation rate of less than 0.2 kg/m²/h. Only Climate E is considered to be favourable for the formation of PShC [3]. The evaporation rates and amounts of the concrete surface water were calculated with Equation 1 as proposed by Uno [3] using the actual conditions measured inside the climate chamber.

\[
E = 5([T_c + 18]^{2.5} - r[T_a + 18]^{2.5})(V + 4) \times 10^{-6}
\]  

Figure 2: The environmental chamber with moulds used for experiments

The exact climate conditions, namely temperature, relative humidity and wind speed, together with the concrete temperature were measured and used to determine the evaporation as mentioned above. The capillary pressure was measured with electronic pressure sensors which were inserted beneath the concrete surface. The tips of the sensors were located at the cracking position just above the triangular insert at the boundary between the different settlement zones. This method was adopted from Slowik [8]. The initial and final setting times of the concrete paste were measured with a Vicat
needle apparatus in accordance of SANS 50196-3 [11]. The concrete was first sieved through a 4.75 mm sieve to leave a mortar suitable for testing [12]. CAD software was used to measure the approximate crack growth on high resolution photos taken regularly. The average settlement of both the 50 and 200 mm zones were measured two hours after the final setting time of the concrete with a steel ruler. The top edge of the transparent Perspex panel was used as a datum line and measurements were taken at the arrows shown in Figure 3. The figure also shows how the differential settlement between the two settlement zones was calculated by using the average of the measured settlement of each settlement zone. The bleeding was measured with two sets of cylinders with depths of 50 and 200 mm respectively, which are identical to the depths in the concrete moulds. A syringe is used to extract the bleeding water that accumulated in the tracks that were created on the surface of the concrete. The extracted water was weighed every 20 minutes. To improve the accuracy of the measurements, the bleeding tests were only conducted at Climate N without the wind. This method was adopted from Josserand [13].

![Figure 3: A schematic and picture of the settlement measurements](image)

A summary of the experimental program is shown in Table 2. The idea of the program was to test two ordinary concrete mixes, one with high and the other with low bleeding/settlement potential, at two environmental conditions, one with high and the other with low evaporation and therefore also potential for PShC. The program together with the moulds served as the ideal platform to investigate to influence of restraint on both PSeC and PShC individually, but also combined. Finally, the influence of adding a low volume of polypropylene fibres to both mixes at only severe environmental conditions was also investigated.

<table>
<thead>
<tr>
<th>Mix name</th>
<th>Description</th>
<th>Environmental conditions used for experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB-Mix</td>
<td>High bleeding mix</td>
<td>Climate E &amp; Climate N</td>
</tr>
<tr>
<td>LB-Mix</td>
<td>Low bleeding mix</td>
<td>Climate E &amp; Climate N</td>
</tr>
<tr>
<td>HBF-Mix</td>
<td>High bleeding mix with fibres</td>
<td>Climate E</td>
</tr>
<tr>
<td>LBF-Mix</td>
<td>Low bleeding mix with fibres</td>
<td>Climate E</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL RESULTS

Figures 4 to 7 show the results of the HB-Mix and LB-Mix for both climates. The figures show the
cumulative amount of evaporation, crack growth and bleeding of both the 50 and 200 mm depths. The capillary pressure and air entry are also shown. Air entry can be identified by the significant drop in capillary pressure. Finally, the figures also show the initial and final setting times of the concrete as well as the time of crack onset, which is defined as the time when the first crack was observed. It should be noted that the evaporation is only valid for free water evaporation [3] and is therefore only applicable until the drying time is reached. The drying time is defined as the time once all the bleeding water at the surface has evaporated and can accurately be identified by the time where capillary pressure starts building up. The graphs of the mixes with fibres at Climate E are not shown, since the results were nearly identical to that of the mixes without fibres as shown in Figures 4 and 5.

Figure 4: Results of the high bleeding mix at Climate E
Figure 5: Results of the low bleeding mix at Climate E

Figure 6: Results of the high bleeding mix at Climate N
4 DISCUSSIONS

4.1 Interaction between PSeC and PShC

Before discussing the interaction between PSeC and PShC it is important to keep in mind the following general fundamental principles involved with each cracking type individually.

- PSeC is caused by settlement and will therefore not form after full settlement has occurred. Since settlement coincides with bleeding, it can be concluded that PSeC ends once bleeding ends. The initial setting time serves as a good indication of when bleeding becomes insignificant (see Figure 8 as confirmation) and therefore also when PSeC ends.
- PShC is caused by capillary pressure build up. PShC is also not possible without air entry into a concrete paste which coincides with the maximum vertical settlement [8].
- Furthermore, it has been shown that for conditions with insignificant PSeC the majority of PShC will occur between the initial and final set of concrete [10].

Figures 4 and 5 show the results of both mixes at Climate E. For both mixes the capillary pressure started to develop rapidly at approximately 30 minutes, close to where the evaporation and the bleeding curves start to separate from each other and thus indicating that the drying time had been reached. Crack onset was observed at 60 minutes and was followed by a significant increase in crack area where more than 70 % of the total crack area developed between the time of crack onset and the initial setting time. In both cases air entry occurred just after the time of crack onset long before the maximum vertical settlement has been reached. Since the first crack occurred long before the initial setting time and also before air entry it can be concluded that cracking was initiated by differential settlement and not plastic shrinkage. The significant crack growth up to the initial setting time is believed to be a result of the both the vertical plastic settlement and horizontal plastic shrinkage.
opening the crack at the same time. Since the initial setting time has not yet been reached, confirms that settlement is still occurring and plastic shrinkage is confirmed by capillary pressure build-up and air entry. The majority of PShC therefore occurred long before it was expected due to the early formation of PSeC together with conditions favourable to PShC. This unexpected and significant crack growth is defined in this paper as “crack jump behaviour” and is discussed in the following section.

Figures 6 and 7 show the results of both mixes at Climate N. For the HB-Mix the capillary pressure starts increasing at approximately 160 minutes with air entry close to the final setting time of 360 minutes. Crack onset is shortly after the initial setting time but since air entry has not yet occurred it is believed that the crack had been formed due to differential settlement. Furthermore, the high amount of bleeding water on the concrete surface and in any possible cracks could also have hidden the crack visually. It is therefore believed that the crack could even have been present before the initial setting time, but could not be seen due to bleeding water. No significant crack growth was observed after the initial crack growth. For the LB-Mix crack onset occurred at 120 minutes long before the start of the capillary pressure build up, air entry or the initial setting time and is therefore clearly PSeC. The capillary pressure started at approximately 140 minutes with air entry between the initial and final setting times. Although the crack continued to grow at a fairly consistent rate until after the final setting time, no “crack jump behaviour” was observed. A possible reason for the crack appearing to grow even after the final setting time is reached, is the evaporation of water from the cracks which increases its visibility. It should be noted that since the capillary pressure sensor of this particular test mould malfunctioned, the results of capillary pressure for identical conditions from another mould with a 50 mm deep settlement section instead of 200 mm is indicated on Figure 7. This is a conservative compromise that does not change the statement that crack onset occurred before capillary pressure build up, since the capillary pressure for this mould will start even earlier than in the normal mould due to less bleeding from the shallower settlement section.

The results of both mixes at Climate N show that PSeC can form without capillary pressure build up or air entry and that air entry does not necessarily indicate the start or presence of a crack for low evaporation rates. It is believed that the air entry does not coincide with the crack onset since the crack is still filled with water and air has therefore not reached the pressure sensor tip. For both mixes the time when capillary pressure started to build up did not correspond to the drying time as predicted by the intersection of the evaporation and bleeding curves. This indicates that Equation 1 underestimates the evaporation at normal environmental conditions. However, this requires further investigation.

4.2 Requirements for “crack jump behaviour”

From the above discussion it is clear that the interaction between PSeC and PShC is significantly influenced by the environmental conditions. This influence is so pronounced that certain environmental and boundary conditions can lead to the so-called “crack jump behaviour”. This behaviour is characterised by the formation of the majority of total early age cracks before the initial setting time of concrete is reached. The requirements for “crack jump behaviour” are:

- Severe environmental conditions with high evaporation rates,
- Boundary conditions that results in differential settlement en therefore PSeC,
- Crack onset long before the initial setting time of the concrete and finally
- By the time of crack onset the capillary pressure should be close to fully developed where air entry has occurred or is on the verge of occurring.

If the conditions are favourable for these requirements, “crack jump behaviour” can occur due to the following reasons:

- The plastic, fluid nature of the concrete paste this long before the initial setting time allows
greater deformation if stressed,

- Once the crack is formed a near maximum capillary pressure is subjected over the entire concrete body and finally
- Both vertical plastic settlement and horizontal plastic shrinkage can open the crack in both directions.

Both the requirements and factors can create a situation, as shown in Figures 4 and 5, where the entire plastic concrete body is highly stressed. Once the crack or weak spot is formed due to settlement there is an overall global relief in pressure across the entire concrete body, which together with the plastic nature of the concrete paste and the combination of PSeC and PShC causes a significant localised deformation at the initial cracking position. However, even though Figures 6 and 7 showed early PSeC, they did not exhibit “crack jump behaviour” since the concrete body was not stressed at the time of crack onset.

4.3 Influence of capillary pressure on settlement

Although it has long been believed that capillary pressure could give additional vertical settlement by forcing the solid particles in the cement paste downwards [14], no literature could be found to prove this. Figure 8 shows the differential settlement of all the tests as measured and calculated according to Figure 3. First only consider the mixes without fibres as the influence of fibres will be discussed in a later section. The climate and therefore the time when capillary pressure started to develop is the only difference between the differential settlement results for the same mix. The results show a significant decrease in differential settlement from Climate E to Climate N. This can only be due to an additional vertical settlement caused by the early development of capillary pressure at Climate E, since the normal gravitational settlement is not influenced by environmental conditions. This provides experimental prove that capillary pressure can result in additional vertical settlement.

![Figure 8: Differential settlement of all the tests conducted](image)

4.4 Influence of settlement/bleeding on PSeC

In general, mixes with low bleeding are more prone to PShC due to a higher concrete paste mobility and capillary pressure build up [8, 14]. However, the question remains whether this also applies to PSeC, where low bleeding mixes results in less settlement and therefore possibly less potential for PSeC. The measure of potential for PSeC in this study is considered to be the differential settlement between the different settlement zones as this is what causes PSeC. Figure 9 shows the results of bleeding for all the mixes with and without fibres for the 50 and 200 mm settlement zones.
Figure 9: Bleeding results for all mixes with and without fibres with depths of 50 and 200 mm

Only the results of the mixes without fibres will be considered in this section, as the influence of fibres will be discussed in the following section. As expected the deeper the concrete specimen the higher the bleeding. The results also suggest that only based on normal gravitational bleeding/settlement both mixes show similar differential settlement potential between the 50 and 200 mm settlement zones. However, as shown in Figure 8 the LB-Mix showed significantly more differential settlement for both climates. This can only be explained by the additional vertical settlement as discussed in Section 4.3, caused by capillary pressure build up, which is believed to be more for low bleeding mixes due to a higher concrete paste mobility and capillary pressure build up. Since the differential settlement is more for low bleeding mixes than for high bleeding mixes, it can be concluded that low bleeding mixes are not only more prone to PShC, but also PSeC. This is confirmed by Figure 10 that shows a significantly higher crack area growth for the LB-Mix compared to the HB-Mix at both climates.

4.5 Influence of fibres on PSeC

Although it has been shown that adding a low volume of synthetic fibres to concrete reduces PShC [3, 4], little is still known about the influence of fibres on PSeC. Figure 10 shows a summary of the crack area growth of all the experiments conducted. Fibres were added to both the high and low bleeding mixes but only tested at Climate E. The results suggest that for extreme environmental conditions fibres have no influence on PSeC or the interaction between PSeC and PShC. This means that the discussions in Sections 4.1 to 4.2 are also valid for concrete containing a low volume (0.6 kg/m$^3$) of synthetic fibres at extreme environmental conditions. This can be explained by the observation that settlement cracking normally occurs before the initial setting time of concrete, which gives a point in time from where the interfacial shear bond stress between the fibres and the matrix starts increasing [10]. Therefore fibres give almost no resistance to PSeC, since there is no bond between the fibres and the matrix during the time where PSeC occurs. In addition, although fibres reduced the amount of bleeding as shown in Figure 9, the differential settlement which causes PSeC remains high as shown in Figure 8. However, the influence of fibres on PSeC at other environmental conditions still need to be investigated.
5 CONCLUSIONS

This paper investigated restraining conditions that promoted both PSeC and PShC in freshly cast concrete with and without a low volume (0.6 kg/m$^3$) of polypropylene fibres. The following useful conclusions can be drawn:

- The interaction between PSeC and PShC is significantly influenced by the environmental conditions.
- For normal environmental conditions with low evaporation rates, PSeC can occur without any capillary pressure build up or air entry, furthermore this indicates that air entry does not accurately indicate the presence of plastic settlement cracks especially at low evaporation rates.
- For extreme environmental conditions with high evaporation rates, PSeC can force the early and unexpected development of the majority of the total cracking before the initial setting time of concrete is reached. This is defined as “crack jump behaviour” and is believed to be due to the combination of the following:
  - The plastic/fluid state of the concrete at this early stage,
  - The nearly fully developed capillary pressure build up at the time of crack onset,
  - The global pressure relief across the entire concrete body once the crack opens which further localises all the deformation at the cracking position and finally
  - The combined effect of PSeC and PShC working together, which therefore opens the crack in both the vertical and horizontal direction.
- The build up of capillary pressure can cause additional vertical settlement.
- Low bleeding mixes are more prone to PSeC, despite having less settlement/bleeding potential.
- The addition of a low volume of polypropylene fibres to concrete at extreme environmental conditions seems to have no significant influence on PSeC or the interaction between PSeC and PShC such as “crack jump behaviour”.
REFERENCES


