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Influence of concrete depth and surface finishing on the cracking of plastic concrete

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HIGHLIGHTS

- Deeper concrete show less severe shrinkage cracks if settlement cracks are absent.
- Deeper concrete show more severe shrinkage cracks if settlement cracks are present.
- Surface finishing temporarily hides shrinkage cracks by only closing the surface crack.

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ABSTRACT

Settlement and shrinkage cracking occurs in plastic concrete once cast up to around the final setting time. This paper reports on the influence of element depth and surface finishing operations on the cracking of plastic concrete. Deeper concrete elements are shown to have less severe shrinkage cracking when no settlement cracking is present, while when combined with settlement cracking at similar cover depths the cracking is more severe in deeper concrete. Surface finishing operations are shown to only close the surface of plastic cracks and not the crack below the surface, therefore temporarily hiding the true severity of the cracking.

1. Introduction

Plastic concrete refers to concrete that has just been cast up to around the final setting time [1,2]. During this period concrete is in transition from a weak fluid or plastic to a solid material and is especially vulnerable to cracking. The two types of cracking that occur in this period for conventional concrete are plastic settlement and plastic shrinkage cracking [3,4]. Cracking due to autogenous shrinkage can also occur in more non-conventional concrete mixes which have water-to-cement ratios lower than 0.4 [1]. This paper only considers conventional concrete mixes and therefore only plastic settlement and plastic shrinkage cracking.

Plastic settlement cracking is caused by differential settlement of the concrete around rigid inclusions such as reinforcing steel [5,6] while plastic shrinkage cracking is caused by a negative pressure build up within the concrete pore system due to evaporation [7,9]. These cracks often occur in flat elements such as pavements, bridge decks, slabs on grade or in buildings that are exposed to conditions with high evaporation rates [10]. There are numerous factors influencing the behaviour and severity of these cracks such as restraint, element depth, setting times, evaporation, bleeding, shrinkage, settlement, mix composition, curing etc [2–11]. In addition, most of these influencing factors are inter- and time dependent, which increases the complexity of conducting experiments on as well as understanding these cracks.

Research regarding the influence of element depth on plastic cracking behaviour is especially rare and most research only considers how depth influences aspects related to plastic cracking and not the cracking itself. For example, Van Dijk and Boardman [12] investigated the settlement at different depths and concluded that the rate and amount of settlement are directly proportional to the depth of a concrete element. Kwak and Ha [13] showed that bleeding and settlement are linked and concluded that deeper concrete elements are more prone to plastic settlement cracking. However, other research has shown that plastic shrinkage cracking

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only starts once the evaporation amount exceeds the total amount of bleeding [11] and therefor the more the bleeding the less the plastic shrinkage cracking [14]. This indicates that the potential for plastic shrinkage cracking could be less in deeper concrete due to a higher bleeding that relieves the internal pore pressure build up for longer.

Another factor that influences the cracking of plastic concrete is surface finishing operations. After the concrete has been placed, consolidated and levelled, the surface is normally further finished by floating and trowelling to either make the concrete aesthetically more acceptable and/or improve its mechanical properties. Bull floating is normally completed before the initial setting time, while power floating and trowelling is completed before the final setting time [15]. In general, floating removes imperfections from the concrete surface and brings cement paste to the surface for trowelling. The type of surface finishing applied depends on the surface quality required in terms of texture and hardness for the specific application [16]. The material type and speed of the blades used for the float and trowel as well as the duration and timing of the floating and trowelling are changed to give the required surface finish.

The surface finishing operations can therefore vary significantly depending on the application, however irrespective of the techniques used the surface finishing operations are applied within the same period where plastic cracking occurs [14,15]. Despite this, research regarding the influence of surface finishing on the cracking of plastic concrete is rare. The ACI 305R-10 [17] guide to hot whether concreting states that plastic shrinkage cracks can be closed by striking the surface on each side of the crack with a float, followed by retrowelling. Dias [18] also mentioned that plastic shrinkage cracks can be closed by trowelling over the cracks as long as the concrete is in the fresh state. However, no experimental prove could be found in literature to confirm this.

It is clear that the influence of depth as well as surface finishing operations on the cracking of plastic concrete is unknown, especially where plastic settlement and plastic shrinkage cracking are combined. With this in mind this paper aims to experimentally investigate the influence of both on firstly only plastic shrinkage cracking and secondly the influence of depth when plastic settlement cracking is combined with plastic shrinkage cracking.

2. Experimental framework

2.1. Moulds and measurements

To study only plastic shrinkage cracking a new dog-bone shaped mould was developed with no inclusions that can induce plastic settlement cracking. This was needed since the standard ASTM C1579 [19] mould that is commonly used for plastic cracking tests was found to include effects of plastic settlement cracking due to the differential settlement caused by its triangular restraints [20]. The shape of the new mould was optimised using finite element modelling and experiments with the aim of maximising stress within the central crack region, while minimising stress concentrations throughout the rest of the mould [21]. The mould contains no inclusions which can result in differential settlement and therefore only induces plastic shrinkage cracking.

However, the mould can easily be modified to include plastic settlement cracking by adding the necessary restraints to the crack region. Fig. 1 shows the new mould where such an inclusion was added in the form of a steel bar. The figure also shows a door or panel on the side of the mould that can be removed to allow the crack to be viewed from the side. The door is only 60 mm wide and as deep as the mould to minimise the concrete area exposed to the environment. More information regarding the development of this mould can be found elsewhere [21] and does not form part of this paper. The mould is further on referred to as the dog-bone cracking mould.

All tests were conducted in a climate chamber to provide controlled environmental conditions as discussed further in Section 2.2. During experiments cracks were monitored from above and the side using two high resolution digital cameras as shown in Fig. 2. Images were taken automatically through glass windows, using Interval Timer Shooting (ITS) with a time interval of 30 s. Glass windows were used to cover the holes to ensure the environmental conditions in the climate chamber remained constant. The ITS for the top camera was activated as the specimens were placed in the climate chamber while the side camera was only activated once the side door was removed. The side door was only removed once the concrete was stiff enough. This varies for different concrete mixtures and climate conditions. A good estimation of when the side door can be removed, is the time the concrete starts to pull away (shrink) from the side of the mould. Once the side door was removed, a Perspex cover was placed on the web as shown in Fig. 1. The purpose of the Perspex cover was to minimise water evaporation from the side surface, especially as a result of the wind, once the door was removed.

The ITS resulted in more than 600 images per specimen. In order to save time the crack was only measured approximately every 5 min from first appearance and during periods of significant crack widening. Once the rate of crack widening decreased the intervals between cracks measurements gradually increased. The crack area was calculated from these digital images using the Digital Image Processing Program (DIPP) ImageJ IJ 1.46r-2012. An example of how the DIPP converts a raw image into a greyscale version is shown in Fig. 3. Firstly, the digital image is scaled according to its true size. Then 10 mm was removed from each side of the crack to account for the influence of the side wall effect [19]. The ASTM C1579 prescribes the removal of 25 mm from each side but it was found that 10 mm is sufficient. Using a tracing tool to select the crack (white area) the DIPP returns the area of the selected crack section. This area is then divided by the total crack length to obtain the average crack width for the required crack section. The cracks of two separate specimens were measured per specific condition and the average of these two specimen are used for further discussion.

In addition to the cracking experiments, the internal pore pressure as well as the settlement and shrinkage were measured in separate square moulds with a depth of 100 and 200 mm respectively using a method similar to Slowik et al. [9]. For the 100 mm deep moulds the measurements of shrinkage and internal pore pressure were taken by embedding shrinkage anchors and steel tubes respectively within the concrete at a single depth of 50 mm as shown in Fig. 4. For the 200 mm deep moulds the shrinkage anchors and steel tubes were embedded at depths of 50, 100 and 150 mm within the same concrete filled mould to allow measurement at different depths. The average of three settlement and shrinkage specimens was used per test, while only one specimen was used per test for the internal pore pressure.

2.2. Mix and environmental condition

A conventional concrete mix suitable for floor and slab construction was used for the experiments. The mix had a slump of 75 mm and a 28 day average compression strength of 38 MPa after being cured in water at 23 °C from an age of 1 day. The mix constituents are shown in Table 1. All tests were conducted in a climate chamber that controlled the ambient temperature at 40 °C, the relative humidity at 10% and the wind speed at 23 km/h. The initial concrete temperature for all test was 23 °C. These conditions are indicative to several arid desert and semi-desert environments around the world and was chosen to result in a high evaporation rate of 1.11 $kg/m^2/h$. Any environment with an evaporation rate of more than 1 $kg/m^2/h$ is considered to be extreme with a high risk in terms of plastic shrinkage cracking and is often associated with high wind speed, low relative humidity's and high temperatures [11,15].

2.3. Test procedures and programme

All materials were placed at an ambient temperature of 23 °C at least one day before mixing to ensure a constant initial concrete temperature for all tests. The mixing and placing process took between 15 and 20 min after which the moulds were placed in the climate chamber, which was also taken as the time zero for all tests. Tests were conducted in separate dog-bone cracking moulds with depths of 100, 150 and 200 mm respectively, while the settlement, shrinkage and internal pore pressure were only tested in moulds with depths of 100 and 200 mm respectively. Tests were also conducted in both the 100 and 200 mm dog-bone cracking moulds where a steel bar with a cover depth of 20 mm was added to the crack region as shown in Fig. 1. An additional test with the 200 mm dog-bone cracking mould was also conducted with a steel bar at a cover depth of 95 mm. After these tests, surface finishing was applied to tests using the 100 mm deep dog-bone cracking mould without embedded steel. The surface of the concrete was finished by continuously smoothing the surface with a regular handheld steel trowel for a period of one minute once the bleeding stopped as well as soon after the appearance of the surface crack.

3. Results and discussion

3.1. Influence of depth on plastic shrinkage cracking

Fig. 5 shows the surface crack widths as measured in the 100, 150 and 200 mm deep dog-bone cracking moulds. These moulds contained no steel bars in the central crack region and therefore did not include the effect of plastic settlement cracking. The results show that the deeper the concrete the less severe the rate and size