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Effect of Various Fibers in Shrinkage cracking and Various Test Methods: A Review

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Abstract - *Plastic concrete is susceptible to develop cracks due to shrinkage in dry and windy conditions. Addition of fibers could reduce propagation of this crack. Plastic shrinkage cracks can be one of the earliest obstacles to appear in concrete, and if left uncontrolled, the durability and life of the structure can be compromised. The main driving mechanisms of plastic cracking have been found to be settlement of solid particles, bleeding, evaporation, capillary action, as well as surface finishing. These, in combination lead to a 3-dimensional volume contraction which if restrained, causes plastic cracking of concrete. The effects of various fibers on the plastic shrinkage crack behavior of cement-based materials have been studied for many years. Most studies have concluded that the fiber type studied has succeeded in controlling the degree of plastic shrinkage cracks. However, there is no clear understanding of which fiber properties have the greatest impact.*

Key Words: Plastic shrinkage, Synthetic, Fibres, Cracking, Concrete, Overlay.

1.INTRODUCTION

As plastic shrinkage cracking can dramatically reduce the durability of a concrete member and causes considerable repair costs annually, a comprehensive understanding of the mechanism of the phenomenon is essential to prevent these damages in future. In its plastic state, which lasts from casting to about 3–8 hours, concrete undergoes volumetric and other changes that strongly influence the properties of the hardened material. Among the volumetric changes is plastic settlement and plastic shrinkage which in combination with other factors may lead to cracking of concrete in this fragile state. The main reason behind plastic shrinkage cracking is considered to be rapid and excessive surface water evaporation of the concrete element in the plastic stage (freshly cast concrete) which in turn leads to the so-called plastic or capillary shrinkage. Consequently, many factors affect the likelihood of plastic shrinkage crack formation such as water-cement ratio, admixture, member size, fines content, concrete surface temperature and ambient conditions (i.e. relative humidity, air temperature and wind velocity). When the pace of water evaporating from the concrete exceeds the rate at which it can be replaced by rising bleed water, a combination of autogenous processes and capillary pressure occurs in the pore structure at the surface, causing the concrete to contract. During plastic state, concrete resists volume changes and other changes that have a significant impact on the properties and behaviour of hardened concrete (Combrinck, Kayondo and Boshoff 2019). The concrete dries if the water evaporates quicker than it evaporates from the concrete. The amount of plastic shrinkage is determined by the amount of evaporation. Furthermore, environmental parameters such as temperature, relative humidity, and wind speed influence evaporation rate. Bleeding is governed by the mixing ratio as well. The mixing ratio is determined by the water/cement ratio as well as the meteorological conditions that the cement matrix is subjected to. (Juarez et al., 2015; Juarez et al., 2015).

2.MAIN FACTORS AFFECTING PLASTIC SHRINKAGE CRACKING

Many factors affect plastic shrinkage in concrete figure 1 summarizes the process of plastic shrinkage cracking and the factors 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.

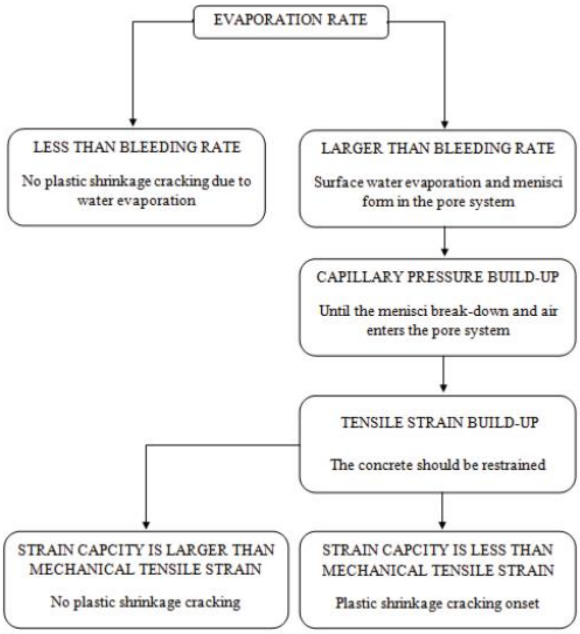

Fig -1: Factors affecting plastic shrinkage.

2.1 Evaporation

The synthetic fibers that are investigated in the studies include polypropylene, polyester, glass, basalt, engineered Once bleed water reaches the surface of concrete, its conversion into the gaseous state is termed as evaporation. The main factors that influence the evaporation rate are: wind speed, relative humidity, air temperature, concrete temperature, difference between air and concrete temperature, as well as solar radiation. In general, the higher the wind speeds, concrete temperature, solar radiation and the lower the relative humidity, the higher the evaporation rate.

2.2 Bleeding

The mechanism of bleeding is driven by consolidating particles(due to free settlement) displacing water towards the surface, where it gathers as a thin film. Bleeding is facilitated by the spaces between the solid particles creating an interconnected system of pores through which water is delivered to the surface. Bleeding is also said to be due to the suction effect caused by capillary pore pressure which occurs once the thin bleed water layer starts to disappear (due to evaporation) [v Dao, P. Dux, P. Morris, L. O'Moore 2010].

2.3 Capillary pressure

Once the concrete surface bleed water starts evaporating up to the point exposing the solid surface, the solid particles at the surface then form a complicated system of menisci [M. Kayondo, R. Combrinck , W.P. Boshoff 2019], as illustrated in Figs. 2 and 3 (C-early & C-later). Once this state is reached, the increasing curvature of the water menisci at the surface causes a negative pressure in the capillary water [V. Slowik, M. Schmidt, R. Fritzsch 2008]. The negative capillary pressures act to draw more water to the surface of concrete, and in the process act to bring the solid particles as close as possible; but this is counteracted by the repulsive forces between the solid particles. Further evaporation at the surface acts to reduce the menisci radii to a threshold value, at which point the local tensile capillary pressures induce a shrinkage strain which if not withheld by the tensile capacity of the still plastic concrete, causes cracking to occur.

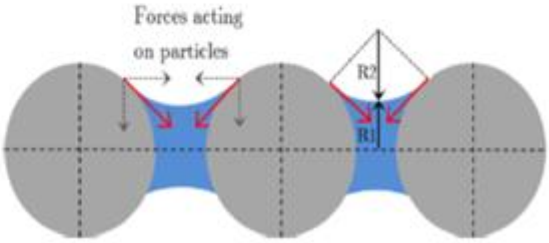

Fig 2-: Illustration of the forces caused by menisci forming in capillary pores

2.4 Hydration

Hydration of concrete progresses and influences several mechanisms of early-age cracking via the different stages such as stiffening, setting/solidification and hardening [M. Schmid, V. Slowik 2013]. As far as plastic shrinkage cracking is concerned, the beginning of hydration means loss of free water on which the plastic nature of concrete is based. This water loss is usually via evaporation, absorption by unsaturated aggregates, formation of hydration products, etc. [P.L.J. Domone, J.M. Illstone 2010]. The progression of hydration gives an indication of the physical state of concrete. The start of the exothermic processes of hydration are preceded by a dormant stage which offers numerous advantages with the handling and placing of concrete. Hydration in plastic concrete is usually associated with arbitrary terms such as initial and final set. These terms give an indication of the end of the stiffening stage and start of setting (initial set), as well as the end of setting stage and start of hardening (final set). In practice, these times are influenced by a number of factors and may greatly vary between laboratory and field tests. Since hydration is characterised by loss of free water, the rate at which this happens directly influences the progression of other mechanisms of plastic shrinkage cracking, such as free settlement, bleeding, and capillary pressure. Ideally, hydration affects the stiffness of plastic concrete, which significantly influences plastic cracking behaviour[S. Ghourchian, M. Wyrzykowski, M. Plamondon, P. Lura 2019].

2.5 Free settlement

The classical gravitation laws largely drive free settlement of solid particles in fresh concrete, and it works in such a way to cause denser packing of the solid particles. Settlement of solid particles displaces water upwards, imparting an upward force due to the viscous drag caused by the flowing water. Free settlement remains active until the point where hydration of cement starts, and can be ceased mechanically before the end of the dormant period if the solid particles physically come in contact with one another hindering further settlement [H.-G. Kwak, S. Ha, W.J. Weiss 2010]. The outcome of this phenomenon is a vertical volume contraction.

3.FIBER MECHANISM IN REDUCING SHRINKAGE CRACKING

The addition of fibers is most widely accepted method for controlling plastic shrinkage cracking.

- The fibers prevent the micro cracks from further propagate on, developing into actual plastic shrinkage cracks by imparting bridging action across the cracks.
- Some types of fibers have also been shown to increase early age tensile strength of the material, thus lowering the possibilities for the stresses to reach the strength of the concrete in the plastic state.
- Fibers added to the fresh mixture tend to reduce the segregation of especially coarser aggregates, which therefore tend to remain closer to the surface. Extensive segregation could also lead to an uneven fiber distribution. It was observed that fine fibers had a better distribution inside the matrix than coarser fibers with a high density which tend to segregate.
- As plastic shrinkage cracking is closely associated with the evaporation rate, several researches also explored the fiber influence on the amount of moisture loss. However, there are a few paradoxes in the literatures. Some studies reported that fibers tend to reduce the quantity of bleeding water by reducing segregation, which succeeds at lower water evaporation rates. On the contrary, other studies reported higher water evaporation rates that were attributed to the development of so-called channels along the fibers. These channels may allow mixing water to rise to the surface, which provides water to replenish the drying surface. (Bertelsen, Ottosen, and Fischer 2020). In this paper, the influence of randomly distributed fibers on cracking caused by plastic shrinkage is discussed (Bertelsen, Ottosen, and Fischer 2020)
- The addition fibers not only to reduce crack formation, but to disperse the cracks so that many micro cracks appear instead of fewer larger ones by improving the strain capacity of the concrete in the plastic state.
- Some types of fibers have also been shown to increase early age tensile strength of the material, thus lowering the possibilities for the stresses to reach the strength of the concrete in the plastic state.
- Fibers added to the fresh mixture tend to reduce the segregation of especially coarser aggregates, which therefore tend to remain closer to the surface. Extensive segregation could also lead to an uneven fiber distribution. It was observed that fine fibers had a better distribution inside the matrix than coarser fibers with a high density which tend to segregate.

4.METHODS OF TESTING

The test methods for evaluating the plastic shrinkage cracking of cement-based materials uses different types of restraints which induce cracking by preventing the specimen from deforming freely and specimen size and shape varies. The test methods used in the studies included in this literature are listed below:

i. ASTM C1579-13 method in which the specimen is prepared in a mould with internal restraints. The concrete specimen is placed in drying settings which prompt plastic shrinkage cracking in the concrete specimen.

The mould used is shown in Fig- 3 and 4.

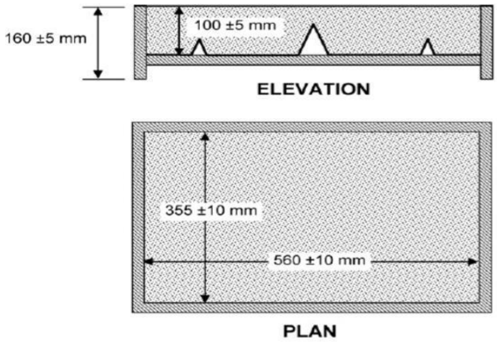

Fig -3: Specimen dimensions

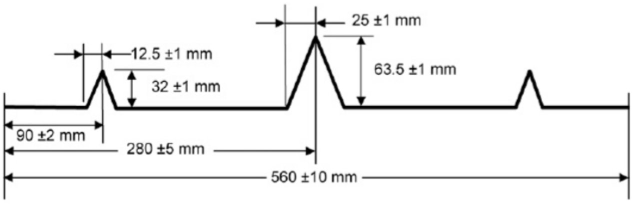

Fig -4: Stress riser geometry

ii. Overlay method with bottom-restraint in which a fresh cement-based overlay is cast over an underlying concrete substrate whose surface is roughened or the surface has protrusions in order to provide uniform bottom-restraints. The cracks formed are then measured using a different technique. Cracks are most commonly measured using microscope or by capturing images of the cracks and analysing images by using computer software. (Banthia and Gupta 2007)

iii. Kraai method with edge-restraints: in this a slab-like specimen cast in a mould with built-in edge-restraints provided along the perimeter. The test specimen is rather thin with a large surface area to volume ratio making it vulnerable to plastic shrinkage cracking as intended. This method often results in scattered crack patterns as shown in Fig. 5.

Fig -5: Kraai method crack pattern

iv. Crack measuring techniques: Plastic shrinkage cracking in concrete structures considered a highly irregular and variable process and, depending on the type of restraint, often results in scattered crack patterns The rates at which the cracks occur can vary significantly depending on parameters such as the test setup, material properties, environmental conditions etc. Thus, studying the formation of plastic shrinkage cracking is challenging, since the material properties are time-dependent and change rapidly over time There is no standardized technique for crack detection and crack measurements; but commonly used are manual measuring techniques using microscopes, handheld lenses etc.; and more advanced image-based techniques such as digital image processing (DIP) and digital image correlation (DIC). With the more advanced techniques, very fine flaws can theoretically be detected on the surface. Hence, there is also a need for a standardized definition of which fineness of such flaws that should be defined as actual cracks.

v. Ring test method: The ring test method set-up developed by Johansen and Dahl consists of two ring-shaped moulds of steel mounted to a steel platform as shown in Fig. 6 [M. Kayondo, R. Combrinck , W.P. Boshoff 2019]. In this method, average crack width is used as a measure of cracking tendency, and the cracking is induced by the radial geometry of the mould.

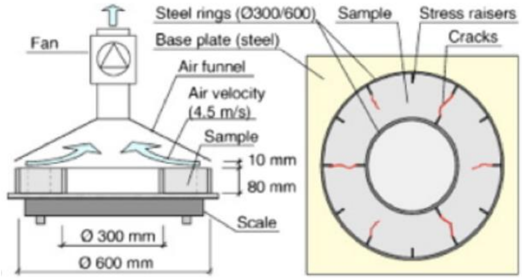

Fig -5: Ring test apparatus

5. INFLUENCE OF FIBERS ON PLASTIC SHRINKAGE

It has been well established that the addition of short, randomly distributed fibers to concrete is an effective method in mitigating plastic shrinkage cracking. The fibers are effective in this regard for two reasons: first, they reduce the overall shrinkage strains and lower the possibility of tensile stresses exceeding tensile strength, and second, the fibers are able to restrict their development if they do occur. The addition of any fiber with a diameter smaller than 40 µm, an aspect ratio above 200, in volume fraction 0.2% - 0.4%, should effectively eliminate plastic shrinkage cracking in concrete. (Branston et al. 2016). For the purpose of comparing the results and analysing the effect of different fibers on plastic shrinkage cracking, the studied fibers are broadly classified into two categories: synthetic fibers and natural fibers. The effectiveness of the fibers was evaluated by considering the reduction in number of cracks and total crack area.

5.1 Polypropylene fiber

After concrete is cast, and if the rate of water evaporation is higher than that of the migration of water from the inside of the fresh concrete to the outer surface, the capillary suction will produce shrinkage, which induces a tensile stress into the fresh concrete. When small quantities of polypropylene fibers are added to concrete, the intertwining system features of the fibers will prevent the large particles from settling. Bleeding may be brought down. Alternatively, because of the cohesion between the fiber and the cement system, the tensile strength of the fresh concrete will increase. (Ma, Tan, and Wu 2002).

The addition of micro synthetic polypropylene fibers had a pronounced effect on the cracking behavior of concrete and reduced the cracking of concrete. The time to form the initial crack was also delayed upon the addition of fibers. The addition of synthetic fibers improves concrete inter-particle locking and consequently reduce plastic settlement and thereby reduce plastic shrinkage. No pronounced effect on capillary pressure was recorded upon the addition of fibers. The addition of fibers also reduced bleeding and evaporation and increased internal temperature of concrete. This increase in temperature maybe because of less bleeding and thus less evaporative cooling. Additionally, internal temperature could have increased because of the heat of hydration in the concrete mix. (Olivier et al. 2018). In general, fiber imparts crack-bridging ability and therefore, contribute against shrinkage cracking occurrence (Islam and Das 2016). It can be observed that the crack width and crack area reduced as the fiber content increased.

Reinforcement using polypropylene fiber reduces settlement and increases the rate and magnitude of evaporation. Fine fibers are more efficient in decreasing settlement, while the longer fibers demonstrate an increase in bleeding. With higher fiber contents, plastic shrinkage crack width is reduced. Multiple secondary cracks are introduced at sufficient fiber contents. The total crack width is significantly decreased. In plastic shrinkage cracking control, coarse fibers are less efficient than finer fiber reinforcement at the same volume.(Qi, Weiss, and Olek 2003) With the addition of 0.1-0.25% (by volume) polypropylene fibers, visibly restrained the crack width compared to control sample. The crack width is reduced by 72-93% with the addition of up to

0.25%. The shrinkage cracking is reduced by 50-99% by the addition of fibers up to 0.3%. (Islam and Das 2016). Polypropylene fibers showed superior ability to control the plastic shrinkage cracks even at volume fractions as low 0.1%. (Shen et al. 2020)

In a comparative study between the performance of mixtures made of various types of polypropylene fibers (polypropylene fibers made in the drawing-wire technique (DW-PP), polypropylene fibers made in two different fibrillated film techniques (FF-PP I fiber and FF-PP II fiber) the difference between them is the different interlinking state between their elements and polypropylene fibers made with Y shape (Y-PP fiber) in mitigating plastic shrinkage cracking, it was concluded that the order of reduction in drying shrinkage cracking is FF-PP I fiber < FF-PP II fiber < Y-PP fiber < DW-PP fiber. When 0.10% or more DW-PP fibers are added into cement mortar, drying shrinkage cracking can be avoided. The results imply that although all the fibers are of polypropylene type, they have different effects on drying shrinkage cracking because of their different geometric shapes (cross-section) (Ma, Tan, and Wu 2002).

5.2 Basalt fiber

The results from previous studies in basalt fiber reinforced concrete do not suggest the fibers are particularly effective in enhancing the post-cracking response of concrete, which is one of the most significant benefits of fiber reinforcement. Literatures suggest that the addition basalt fibers without any protective coating does not have long-term durability in alkaline atmosphere. One study (Branston et al. 2016) suggests that the effectiveness of varieties of basalt fibers (bundle dispersion fibers, filament dispersion fibers, and minibars) in inhibiting plastic shrinkage cracking in concrete were assessed. It is clear that the benefit of the fibers is not just of their ability to reduce free shrinkage strain. The fibers are effect partly, due to their ability to bridge cracks and restrict their growth. Preliminary testing showed that at the lowest dosage of 0.05% by volume, 25mm filament dispersion fibers completely eliminated shrinkage cracking in the concrete. 25mm filament dispersion fibers had the greatest effect in reducing crack area and width. Nevertheless, literatures suggests that high-modulus fibers such as basalt affects workability when compared to low-modulus fibers. Therefore, the application of basalt fibers for plastic shrinkage crack control is likely best suited for general-use concrete, where w/c ratio is often high enough that the fibers will not require additional measures to restore workability (Branston et al. 2016).

5.3 Natural fibers

In a comparative study between the performance of mixtures made of natural fibers (flax & agave lechuguilla) and PVA fibers in mitigating plastic shrinkage cracking, the results obtained suggest that both natural fibers were successful in regulating plastic shrinkage cracking of concrete like the commercially available synthetic fibers. The crack evolution was influenced by the fibers' geometrical characteristics, such as its length and aspect ratio. An increment in aspect ratio promoted the reduction of crack width and propagation. Natural fibers have better ability to absorb water, which may cause internal curing of the concrete, causing additional reduction in the cracking causedby autogenous shrinkage (Juarez et al. 2015).

The addition of flax fibers to concrete, new bridging forces are developed due to the presence of fibers, which prevent crack propagation. Also, the addition of flax fibers lowers the bleeding, which improves the stiffness of fresh concrete. The increase in fiber lengths leads to the reduction of the rate and amplitude of plastic shrinkage, which may be attributedto the large area taken up by fibers that holds particles of concrete together. There is stress concentration localized above the stress riser using the shorter length of fibers. In fact, longer fibers permit achieving an adequate stress transmission and a decreasing of the stress concentration across the crack. The horizontal plastic shrinkage of concrete decreases with the increase of the percentage and length of flax fibers. No macro cracks have been observed with mixtures containing flax fibers due to the reduction of stress concentration above the stress riser of the mould. An increase in the strain distribution has also been observed at the specimen surface with an increase of the fiber length indicating a better stress transfer (Kouta, Saliba, and Saiyouri 2020)

6. CONCLUSIONS

Plastic shrinkage cracking is a complex interaction of several variables that may change under different circumstances and conditions at the very early ages. These variables have a direct influence on the evaporation, capillary pressure build-up rate and the duration of dormant period. After a thorough review on the subject of plastic cracking of concrete, the following remarks are derived:

- Plastic cracking of concrete is not a new phenomenon; it is deeply established in literature dating back over 60 years ago. However, over the years, the understanding of the subject of plastic cracking has been enriched, relative to the advancement of concrete technologies.
- Fundamentally, mechanisms such as settlement, bleeding, evaporation, hydration, and capillary pressure are all proportionately known to influence plastic cracking of concrete (plastic settlement cracking and plastic shrinkage cracking).
- The currently existing test methods (for the respective fundamental mechanisms), simulations, and models have widened the understanding and prediction of plastic shrinkage cracking both in the laboratory and in the field. Based on these,

preventative measures have been developed to mitigate plastic cracking of concrete.

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