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Study on the Effect of Fibers on Concrete Shrinkage

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Abstract - *Plastic shrinkage cracking is possibly one of the earliest damages which arise in concrete, and it is capable of affecting the durability and life span of a structure, if not prevented. Severe early-age cracking may propagate further later and allow the entry of destructive agents such as water and chlorides leading to corrosion of the steel rebars and premature damage of concrete. The incorporation fibers in concrete for controlling plastic shrinkage cracking has shown good results. The influence of a wide variety of fibers on the plastic shrinkage cracking behavior of cement-based materials have been studied over the years. Most of the studies concluded that the investigated fiber type was successful in controlling the degree of plastic shrinkage cracking. However, there is no conclusive findings on which fiber properties are most influential. The aim of this study is to reveal how various fibers influence the plastic shrinkage cracking behavior of concrete.*

Key Words: Plastic shrinkage, Fibres, Cracking, Concrete, Durability

1.INTRODUCTION

Concrete withstand volumetric and other changes during the plastic state that significantly determines the characteristics and behaviours of the hardened concrete (Kayondo, Combrinck, and Boshoff 2019). Plastic shrinkage is the contraction of concrete that takes place while it is in plastic form. If moisture from concrete evaporates at a faster degree than bleeding, the concrete will dry out early, resulting in cracking. The extent of the plastic shrinkage is determined by the degree of evaporation. The evaporation rate in turn is determined by environmental factors such as temperature, relative humidity and wind velocity. Moreover, bleeding depends on the mixture proportion, which can vary depending on the w/c ratio and the weather conditions to which the cementitious matrix is exposed. (Juarez et al. 2015)

1.1 Fiber mechanisms in controlling plastic shrinkage cracking

The addition of randomly distributed fibers is a widely accepted technique for controlling plastic shrinkage cracking.

- The role of adding fibers is reported 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.
- The fibers prevent the micro cracks from further propagation, 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). There are several precautionary measures to prevent plastic shrinkage cracking in cement-based materials. The most effective technique for mitigating plastic shrinkage cracking is by preventing the water evaporation from the surface. Consequently, stopping the surface from excessive drying. The addition of randomly distributed fibers is known to be especially effective. In this paper, the influence of randomly distributed fibers on cracking caused by plastic shrinkage is discussed (Bertelsen, Ottosen, and Fischer 2020)

2. MATERIALS

Fibers of different materials, geometry, dimensions, mechanical properties and other different characteristics are used in different studies to investigate its influence on the plastic shrinkage cracking behavior of cement-based materials. The most commonly used fibers include polymeric, glass, basalt, and natural fibers. Cementitious materials in these studies include mortar and concrete. Also, in some studies, these cementitious materials also have additives other than the conventional ingredients such as mineral admixtures, chemical admixtures such as shrinkage reducing admixtures, super absorbent polymers, etc.

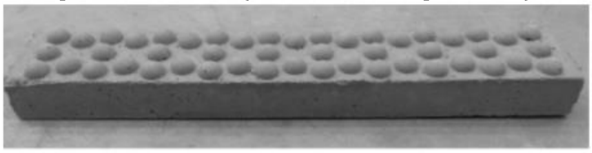
Table -1: Details of the materials used test methods in the studies included in this review

Cementitious materials	Fiber material	Fiber content	Reference
Concrete	Polypropylene micro fiber	900g/m^3 of concrete	(Olivier et al. 2018)
Concrete/ mortar	Basalt fibers: Bundle dispersion fibers	0.05, 0.1,0.3,0.5 % by volume of concrete	(Branston et al. 2016)
	Filament dispersion fibers		
	Minibars		
Mortar	Natural fibers – flax & agave lechuguilla	0.1, 0.7% by volume of concrete	(Juarez et al. 2015)
	Synthetic (PVA) fibers		
Earth concrete	Natural flax fibers	0.3% & 0.6% by volume of concrete	(Kouta, Saliba, and Saiyouri 2020)
Concrete	Polypropylene fiber	0.1%, 0.15%, 0.2%, 0.25%, 0.3% by volume of concrete	(Islam and Das 2016)
Mortar	Polypropylene (PP)	0.1%, 0.2% (PP) 0.2%, 0.5%, 1%, 2% (R-PE) by volume of concrete	(Bertelsen, Ottosen, and Fischer 2019)
	Recycled polyethylene fibers (R-PE)		
Mortar	Kraft pulp fiber: Unmodified fiber	0.5, 1, 2% by mass of cement	(Booya et al. 2019)
	Mechanically modified fiber		
	Chemically treated fiber		
Mortar	Polypropylene fibers	0.05, 0.1, 0.15% by volume of concrete	(Ma, Tan, and Wu 2002)
Mortar	Polypropylene fiber	0%, 0.05% & 0.10% by volume of concrete	(Pelisser et al. 2010)
	Glass fiber		
	Polyethylene terephthalate fiber		
	Nylon fiber		
Concrete	Fine fibrillated polypropylene fibers (FP),	0.05, 0.1, 0.2, and 0.3% (FP) 0.1, 0.2, 0.3, 0.5, and 0.7% (MP) by volume of concrete	(Qi, Weiss, and Olek 2003)
	Coarse monofilament polypropylene fiber (MP)		
Concrete	Polyacrylonitrile (PAN)	PAN-0.04% PP-0.1% GLS-0.02% PE-0.07 % by volume of concrete	(Sirajuddin 2018)
	Polypropylene (PP)		
	Glass fibres (GL)		
	Polyester fibres (PE)		
Concrete	Hooked steel	0.5% by volume of concrete	(Sivakumar and Santhanam 2007)
	Polypropylene		
	Polyester		
	Glass		

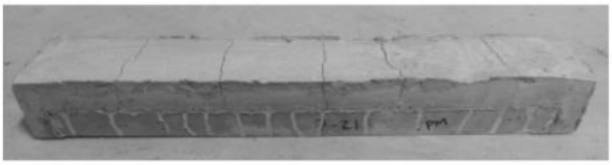
3. TEST METHODS

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. 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)



(a) High strength concrete restraining element



(b) Mortar overlay

Fig -1: Restrained shrinkage test by overlay method (Branston et al. 2016)

ii. 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- 2 and 3.

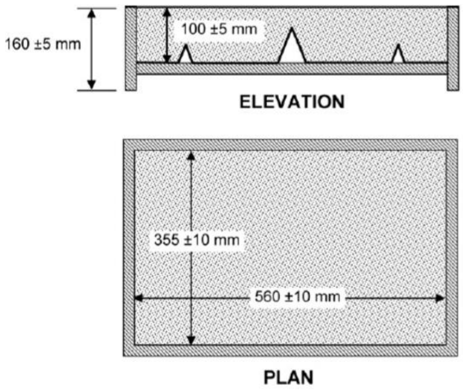


Fig -2: Specimen dimensions

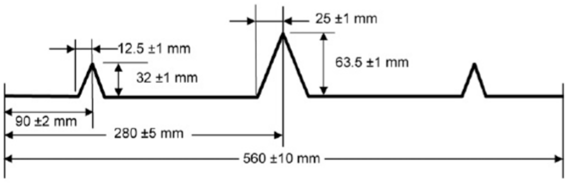


Fig -3: Stress riser geometry

The width of the crack is then measured using an instrument which has a least count of 0.05 mm.

iii. Kraai method in which a specimen of concrete is prepared in a mould which has edge-restraints offered by thin panels throughout the edge of the mould. The dimensions of specimens are commonly 900 x 600 x 19 mm. The edge restraints provided consists of L-shaped hardware cloth/wire mesh, horizontal bolts or steel blocks located on the base of the mould at a constant width.

4. 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.

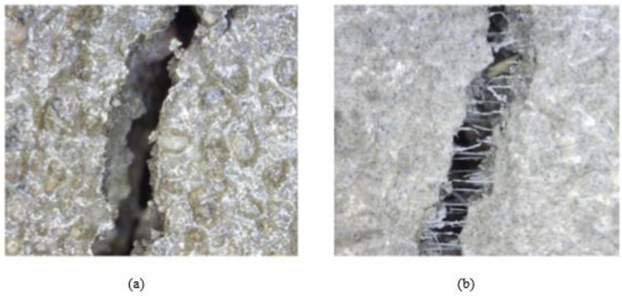


Fig -4: Crack development with (a) and without (b) fibers (Booya et al. 2019)

3.1 Effect of synthetic fibers on plastic shrinkage

The synthetic fibers that are investigated in the studies include polypropylene, polyester, glass, basalt, engineered kraft pulp fiber, PET (polyethylene terephthalate) fiber, nylon fiber and PAN (polyacrylonitrile) fibres. Among these fibers, several variations of fibers of the same materials are also used such as fibers of same material but different geometry or lengths.

3.1.1 Effect of polypropylene fibers on plastic shrinkage

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 (cumulative) 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).

3.1.2 Effect of basalt fibers on plastic shrinkage

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).

3.1.3 Comparative study between the effects of various synthetic fibers on plastic shrinkage

It can be observed polypropylene fibers are the most effective to reduce cracking in comparison with glass, PET and nylon fibers. Glass and PET showed similar results. On the other hand, nylon fibers were least effective. The difference in efficiencies between fibers is probably due to distinct characteristics in the fabrication process and consequently the fiber/cement interaction. It can be inferred that fiber volume fraction of 0.1% or greater in concrete plates are necessary to reduce crack openings significantly. (Pelisser et al. 2010)

In a comparative study between the performance of mixtures made of various synthetic fibers ((polypropylene, polyester, glass and PAN), it was observed that at the dosages recommended by the suppliers, polyester and polypropylene performed much better than glass and PAN basically due to the higher number of fibres that imparts bridging action and reduces settlement in concrete. At the recommended dosages (PAN-0.45, PP-0.9 kg/m3), the polypropylene and polyester fibres completely eliminated cracking in the mix whereas the dosages of the PAN and GLS had to be increased beyond the recommended dosages (GLS-0.6, PE-0.9 kg/m3) to about 1.2 kg/m3 for them to completely eliminate the cracking. It is also seen that the fibre addition delays crack initiation, if any, reflecting the effect of the lower evaporation and crack bridging, which is more effective when larger number of fibres are present. Due to the incorporation of fibres, the moisture loss is seen to reduce with no substantial difference due to the fibre type. The lower evaporation could be attributed to the impediment of settlement by the fibres that inhibits the upward movement of water. (Sirajuddin 2018)

In another similar study, it was also observed that polypropylene fiber addition was more effective than steel fiber against shrinkage cracking. In comparison with steel fiber reinforced concrete, hybrid fiber concrete showed superior crack control features. The reduction in crack width using hybrid fiber combination significantly contributed to the reduction of overall crack area. Plastic shrinkage cracking was reduced by 50 - 99% when 0.5% fiber was added to concrete blending both steel and polypropylene fibres.

The improved performance of hybrid fiber combination can be attributed to the increase in fiber availability compared to the steel fiber concrete, since all non-metallic fiber had considerably lower specific gravity than steel. The increase in fiber availability reduces the fiber spacing and also the propensity for crack origination. However, the performance is not linked only to the fiber availability. Amongst the hybrid fiber concrete, the performance was further affected by the length and stiffness of the non-metallic fibers. Polyester and polypropylene fibers performed better than glass. This could be explained by the differences in stiffness of these fibers. Polyester and polypropylene fibers have much lower elastic modulus and are much longer compared to glass fibers, the short glass fibers could have got pulled out of the matrix even at the low stress levels, as the bond between fiber and matrix would not have developed sufficiently. The addition and increase in the fiber content in concrete resulted in an appreciable crack width reduction. However, it also caused a decrease in workability of concrete due to the presence of larger number for fibers (since non-metallic fibers have a lower specific gravity). This causes balling and resultant trapping of free water. This negative effect restricts the maximum dosage of polypropylene and polyester fibers to an optimal level of 0.25% based on a workability range of 50-75mm. In the case of glass fibers, the increase in fiber dosage up to 0.38% does not affect the workability (Sivakumar and Santhanam 2007).

3.2 Effect of natural fibers on plastic shrinkage

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 caused by 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 attributed to 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)

4. CONCLUSIONS

A review covering existing research on plastic shrinkage in fiber-reinforced cement-based materials was carried out to analyse the influence of the addition of different types of fibers. Several fibers of different materials, geometries, shapes and mechanical properties have been investigated. In this literature, several test methods for determining restrained plastic shrinkage cracking of concrete is discussed. The main difference between these methods is the variation is specimen size and geometry, type of restraints, environmental conditions where the testing is carried out and the crack measuring techniques. The effectiveness of fibers in reducing plastic shrinkage cracking was evaluated by considering the crack parameters such as max crack width, length area and number of cracks together with other factors such as fiber content, fiber geometry, and dimensions. The following conclusions can be made from the study:

i. Polypropylene fibers are the most effective to reduce cracking in comparison with other synthetic fibers.

ii. Compared to steel fiber reinforced concrete, hybrid fiber concrete (polypropylene fiber used in combination with steel fiber) showed better crack control features.

iii. Among fibers of same material but different geometry, crack reduction is improved with increase in surface area and increased number of uniformly spaced filaments in fibers.

iv. Natural fibers such as flax & agave lechuguilla are effective in controlling restrained plastic shrinkage cracking like the commercially available synthetic fibers.

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