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A Review on the Effect of Natural Fibers on Plastic Shrinkage of Concrete

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Abstract - *Plastic shrinkage cracking is one of the earliest forms of concrete cracking, occurring in its plastic state. Concrete structures with large exposed surface areas are prone to plastic shrinkage cracking, resulting in premature durability issues. Controlling concrete plastic shrinkage cracking is crucial for developing durable concrete structures with longer service life and fewer maintenance costs. The addition of arbitrary distributed fibers is a successful technique to mitigate plastic shrinkage cracking. Natural fibers have been utilized to assess their potential for reducing plastic shrinkage. Natural fibers are widely available, renewable, biodegradable, with low cost and specialized qualities. Many of them have represented adequate behavior in controlling cracks caused by plastic shrinkage. So, natural fibers can be a feasible technological option to mitigate plastic shrinkage cracks and it is possible to consider them as a potential replacement for some synthetic fibers. Various studies show that natural fibers are effective in controlling plastic shrinkage cracking in concrete, which has been summarized in this literature.*

***Key Words*: Plastic shrinkage, Durability, Cracking, Natural fibers, Concrete**

1. INTRODUCTION

Concrete is prone to shrink within the first few hours after casting, while still in a plastic state, if the rate at which water evaporation from the surface exceeds the bleeding rate in concrete. Cracks occur to relieve the tensile stresses that develop when such shrinkage is restrained [3]. Such cracks can further propagate and allow the entry of aggressive agents like chlorides, water, etc., leading to the corrosion of the reinforcement. Plastic shrinkage cracks may reduce the durability and lead to premature deterioration of the structures [2]. Low ambient humidity, high wind speeds, and high temperatures, might increase the risk of plastic shrinkage cracking on the surfaces of structural and non-structural concrete, as well as Portland-cement-based mortar [6].The primary factors that influence plastic shrinkage cracking are bleeding and evaporation of internal concrete moisture [7]. Water menisci form between solid particles when the layer of bleed water evaporates from the surface as a result capillary pressure starts to build up. This capillary pressure causes the contraction of concrete and if a critical limit is reached, cracks may [2]. Plastic shrinkage cracking occurs in structures with large surface areas such as bridge deck, parking slabs, industrial floors, tunnel lining and thin concrete surface repairs.

1.1 Mitigation measures

Achieving a balance between bleeding of concrete and evaporation of bleed water is a key for the mitigation of plastic shrinkage of concrete. The plastic shrinkage cracking can be mitigated through an appropriate mix design, usage of superabsorbent polymers, liquid and mineral admixtures etc. The ultimate way to control plastic shrinkage cracking is to prevent the surface from extensive drying. Apart from the material-based mitigation measures, other approaches like wind breakers, temperature control of both material and environment, water spray(fogging) can be utilised [7]. The addition of randomly oriented fibers is a widely adopted method for the mitigation of the plastic shrinkage in concrete [2]. Being inexpensive and due to its regional availability, natural fibers can be a feasible option to control plastic shrinkage cracking. In the present study, the emphasis is on the influence of natural fibers on cracking caused by plastic shrinkage.

1.2 Influence of fibers in controlling plastic shrinkage cracking

Addition of appropriate percentage of randomly oriented fibers in the concrete matrix can give good results in controlling plastic shrinkage cracking. By improving the strain capacity of fresh mixture, fibres in concrete can not only minimise crack formation but also spread cracks so that numerous micro cracks appear instead of fewer larger ones. Fibers also prevent the propagation of micro cracks by providing bridging forces across the cracks. Fibres added to the fresh concrete tend to reduce the segregation of especially coarser aggregates, keeping them closer to the surface. Some types of fibres have shown good results in improving the early age tensile strength of the material, thus lowering the chances for the stresses to reach the strength of the concrete in its plastic state [2]. Natural fibers have the potential to control plastic shrinkage of concrete. They are abundant, inexpensive and mostly underutilized resources. They are generally produced as waste by-product of agricultural or industrial processes [3]. Even though production of synthetic fibers is expensive, their efficiency in reducing plastic shrinkage cracking is widely known. However, very few studies were conducted to determine the effect of natural fibers in controlling plastic shrinkage cracks in concrete. Inexpensive fibres such as coir, sisal, jute, flax, lechuguilla, and others may be a viable technical option for mitigating concrete cracking caused by plastic shrinkage. In this paper, the influence of natural fibers on cracking caused by plastic shrinkage is discussed.

2. MATERIALS

Various studies were conducted with different types of fibers to prevent the plastic shrinkage cracking in cement-based materials. Fibres of different geometries, mechanical properties shapes and volume fractions were used. Animal-based, mineral-derived, and plant-based are the three types of natural fibres usually used in concrete reinforcement. Various forms of natural fibers have been investigated in some studies. Natural fibres such as cellulose, sisal, coconut fiber, flax, Lechuguilla etc. are among them. Other materials used in the studies conducted include cement, aggregates, other binder types like silica fume, fly ash, GGBS for cement replacement, mineral admixtures, chemical admixtures like shrinkage reducing admixtures. Some of the plant based natural fibres are the following [11].

2.1 Bast fiber

Bast fibres are obtained from the outer bark of the plant's stem and are removed through the retting process. Jute, flax , kenaf etc are some of the examples of these fibers. Bast fibres have long fibre bundles with high tensile strength, which is why they are traditionally used to make yarn, cloth, rope, sacks, and so on.

2.2 Leaf fiber

Leaf fibres are coarse and hard fibres. They are usually obtained by hand scraping from leaf tissues followed by the beating/retting process. These fibers are having relatively high strength due to which they are used to manufacture of ropes, textiles, carpets, and mats. Examples are sisal, caroa, henequen and pineapple.

2.3 Seed fiber

One of the best examples of seed fiber is coir fiber. These lightweight and robust fibres are mostly utilised in the manufacture of ropes, matting, sacks, brush, geotextiles, and other products. Other examples are cotton, kapok and milkweed floss which are soft, buoyant materials that are commonly utilised in textile, water safety equipment, insulation, upholstery, and mattress products.

2.4 Stalk fiber

These are plant stalk fibres that are typically taken fromeggplant, sunflower, wood, and the straw of various grain crops such as barley, wheat, rice, and so on.

2.5 Grass and other fibre crop residue

Ryegrass, elephant grass switchgrass and bamboo are some of the important sources of fibres. fibrous crop residues such as pulse seed coat, peanut shell, hazelnut husk, corn husk, millet stover etc. can be used as fibre reinforcements in concrete.

2.6 Wood and specialty fibres

Wood fibres are obtained from a wide range of trees. As a result, they are in great abundance all over the world. The two main types of wood fibres are softwood and hardwood. The main distinction between these two types is that, while softwood fibres are often longer, hardwood fibres have thicker and tougher cell walls. Specialty cellulose fibres, on the other hand, are industrially processed plant-based natural fibres with unique properties such as bond strengthening and alkali resistance. Furthermore, the quality-controlled manufacture of these fibres ensures that the enormous range in geometrical and mechanical properties associated with unprocessed plant-based fibres is considerably reduced

3. METHODS

Various test methods adopt different internal and external restraints to induce plastic shrinkage cracking by preventing the specimen deforms freely. The test methods used to determine plastic shrinkage cracking in the studies included in this review are as follows:

3.1 Overlay method

Overlay method with bottom restraint is a method in which concrete substrates are made and over which cement-based materials are cast. This method employs a bottom restriction to promote plastic shrinkage cracking. Regular patterns of semicircular protuberances are provided over the substrate as restraint to induce cracking [12].

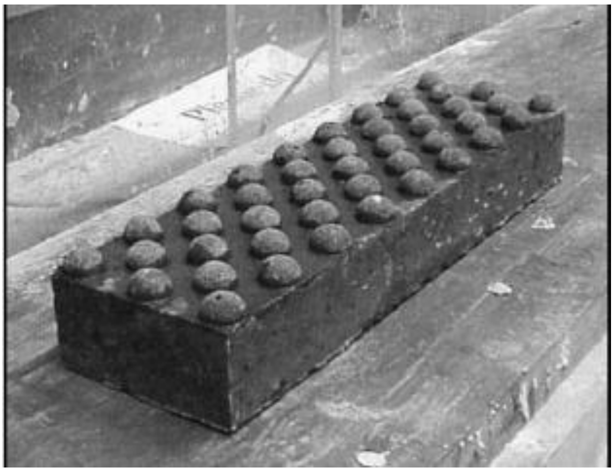

Fig-1: A substrate base for overlay method

3.2 ASTM C1579 method

ASTM C1579 method with stress risers is the standard test method for evaluating plastic shrinkage cracking of restrained fibre reinforced concrete. This test method compares surface cracking of fibre reinforced concrete panels to surface cracking of control concrete panels subjected to specified constraint conditions. This method aims to quantify the relative performance of a given fresh concrete mixture by controlling atmospheric variables. The specimen is cast in a mould of internal restraints. This mould is having a depth of 100±5mm and rectangular dimensions of 355±10mm by 560±15mm. The central riser is 64±2mm high and serves as an initiation point for cracking [13].

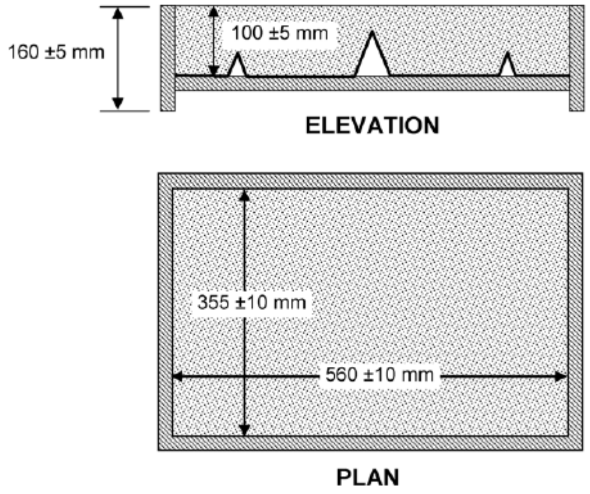

Fig-2: Specimen used in ASTM C1579 method

3.3 J ring test (NT Build 433)

This is a method developed by Johansen and Dahl. Three identical moulds, each with two concentric steel rings are used in this test method. Stress ribs induces cracking in concrete and the length and width of the crack are measured using a digital microscope [10].

3.4 Kraai method

Kraai method with edge restraints is a method in which slab like specimen is cast in a mould and are provided with edge restraints. The specimen is thin with a large surface area to volume ratio. Specimen of size 900 x600 x150 mm are used. [14]. Edge-restraints are positioned all through the entire perimeter of the mould and are made up of of L-shaped hardware cloth/wire mesh horizontal bolts or steel blocks placed at a fixed distance on the bottom of the mould. To maximize plastic shrinkage, the specimen was kept in a chamber and exposed to a constant temperature of 28 2 C, a relative humidity of 40 5%, and a wind velocity of 6 m/s for 24 hours. After 24 hours, the width and length of cracks were evaluated with a 0.01-mm precision using a microscope. The method is often used to test cement or mortar materials rather than concrete due to the small height of the slab.

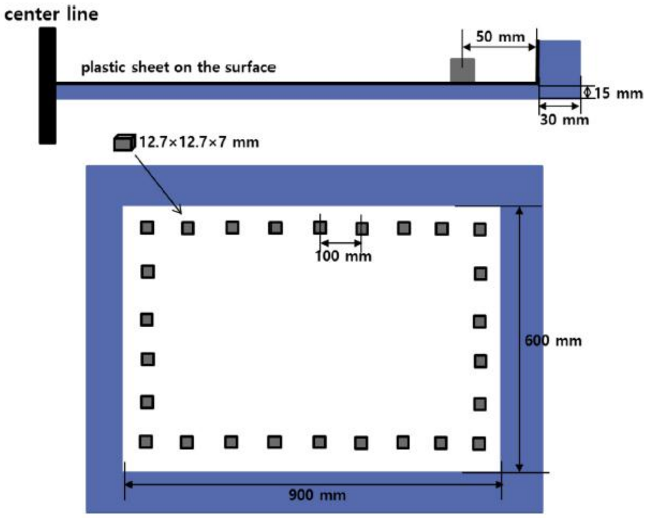

Fig-3- Schematic diagram of kraai method

3.4 ASTM C-1581

It specifies the laboratory determination of the age at cracking and induced tensile stress properties of mortar or concrete specimens subjected to controlled shrinkage. In a circular mould, a sample of freshly mixed mortar or concrete is compacted around an instrumented steel ring. From the time of casting, the compressive strain created in the steel ring due to shrinkage of the mortar or concrete specimen is measured with four strain gauges. A quick decrease in the steel ring strain indicates cracking of the test material. The age at cracking and rate of tensile stress development in the test specimen show the material's cracking resistance under controlled shrinkage. This test method can be used to determine the relative likelihood of early-age cracking in various cementitious mixtures and to aid in the selection of cement-based materials that are less prone to cracking under retrained shrinkage. The actual cracking tendency in service is determined by a variety of factors, including structure type, degree of restraint, degree of property development, construction and curing processes, and environment factors [16].

Fig-4- Restrained ring mould

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

Cementitious materials	Fiber materials	Fiber content	Test method	References
Mortar	Flax	0.05, 0.1, 0.3% by volume of mortar	Overlay	Boghossian E.et al.
Mortar	Flax & agave lechuguilla	0.1,0.7 % by volume of mortar	Overlay	Juarez et al.
Earth concrete	Flax	0.3,0.6 % by volume of mortar	ASTM C1579	Kouta N.et al.
Mortar	Sisal	0.1,0.2, 0.5% by volume of mortar	J ring test	Filho R. et al.
Mortar	Coconut fiber	0.5% by volume of mortar	J ring test	Filho R. et al.
Foam concrete	coir	0.3,0.4, 0.5% by volume of concrete	ASTM C1579	Raj B. et al.
Mortar	Pig hair	8 kg/m³ of mortar	ASTM C1579	Letelier et al.

4. CRACK MEASURING TECHNIQUES

The rate at which cracks develop might vary considerably depending on factors such as test setup, material properties, climatic conditions, and so on. Thus, understanding the formation of plastic shrinkage cracking is difficult because material properties vary rapidly over time. There is no standard technique for crack detection and measurement. manual measuring techniques are microscopes, handheld lenses etc. [2]. The use of several kinds of optical lenses or microscopes is included in the manual procedures. Crack lengths were measured in several studies by placing a string along the length of the crack and measuring it. The total crack area is usually calculated by multiplying the average value of the crack widths by the length of the crack, and the accuracy of the results is thus dependent on the number of measurements [17]. The benefits of using these manual approaches are their simplicity and ability to be performed on-site. They are, on the contrary, criticised for being subjective, time consuming, and complicating constant monitoring. The use of optical cameras to capture high-resolution images of the specimen surface, which are then analysed by various types of software, is one of the more advanced image-based techniques. DIP (Digital Image Processing) techniques operate by processing photos and calculating crack dimensions based on pixels [18**].** DIC technique is considered to be more useful than the DIP method since it permits not only automatic computation of crack widths, but also analysis of surface strain and displacement fields. However, there are still obstacles in using the DIC method to study plastic shrinkage crack formation since recording surface displacements requires a high-contrast surface pattern, which is difficult to put on a wet surface with bleeding water **(Bertelsen et al., 2020).**

5. INFLUENCE OF NATURAL FIBERS ON PLASTIC SHRINKAGE

Very few studies have been conducted to investigate the effect of natural fibers on the plastic shrinkage in concrete. This may be probably due the chances of degradation and low durability of them inside highly alkaline cement-based matrix. Natural fibers are hydrophilic in nature so that they absorb lots of water compared to other types of fibers. The natural fibers that are investigated in the studies include sisal, coconut fibers, flax, Lechuguilla, kraft pulp fibers. Among these fibres, several variations in geometry, aspect ratio, volume fraction were considered.

5.1 EFFECT OF FLAX FIBERS ON PLASTIC SHRINKAGE

Reduction in plastic shrinkage was observed with the addition of flax fibers in cement -based composites. The observations by Boghossian et al. show that when flax fibres were added at a volume fraction of 0.1 percent, the total crack area on the surface of specimens within the first 24 hours and the maximum crack widths were reduced by more than 95% and 90% compared to plain mortar specimens. These reductions were 99.5 percent and 98.5 percent, respectively, at a volume fraction of 0.3 percent. When optimal length was compared, flax fibres performed better than other synthetic fibres, especially monofilament polypropylene, fibrillated polypropylene, and alkali resistant glass fibres, in terms of reducing total crack area and limiting crack widths in fresh mortar specimens. This may be due to the superior quality of flax fibers in improving the tensile capacity of fresh mortar. The hydrophilic nature of flax fibers improve the bond between fiber and fresh mortar. An increase in volume fraction also led to the reduction of plastic shrinkage cracking [3]. In a comparative study between PVA fibers and natural fibers(flax and Lechuguilla) in the mitigation of plastic shrinkage cracking, flax fibres at 0.7% volume fraction of mortar presented adequate behaviour in reducing plastic shrinkage cracking compared to other two fibers. Addition of flax fibers at a volume fraction of 0.7% yielded the best result by lowering the total crack area, cumulative crack width, widest crack observed by 98%,97% and 78% respectively. Higher volume fraction is more effective than fiber length in minimising the plastic shrinkage cracking. Increase in aspect ratio decreases the evolution of plastic shrinkage cracking [6]. Plastic shrinkage of earth concrete can be reduced by increasing the percentage and length of flax fibres. The plastic shrinkage is decreased to 2 to 2.4 times with the incorporation of 0.3% and 0.6% of flax fibers respectively compared to the control mix. Increasing the fiber length led to the decrease in rate and amplitude of plastic shrinkage. The effect of fiber lengths is more noticeable for the formulation with 0.3% of fibers. Addition of flax fibers also reduced the cracking in earth concrete in its plastic. state. During the first 24 hours after casting, no macro-cracks were noticed due to the decrease in the stress concentration above the stress riser of the mould [8].

5.2 EFFECT OF SISAL FIBERS ON PLASTIC SHRINKAGE

Filho R. et al. observed that adding 0.2 percent volume fraction of 25mm sisal fibre to the mortar matrix greatly reduced free plastic shrinkage. Sisal fibers give restraint to the sliding of the matrix by means of frictional resistance. The addition of 0.2% sisal fibers reduced the restrained plastic shrinkage by delaying the initial cracking and effectively controlling the crack development in the composite in its plastic state. The inclusion of sisal fibers is effective in delaying first crack appearance which may be attributed to the high elastic modulus of fibers compared to the cementitious matrix, in addition to its ability to provide bridging forces across the cracks. The addition of 0.2% and 0.1% of sisal fibers (25mm long) resulted in the reduction of free plastic shrinkage of the mortar mixes by 29.6% and 24.1% respectively. The first crack appeared in the matrix 90 min after placing the mix, whereas with the addition of 0.5% volume fraction of sisal fibers, it appeared after 180 min. Fibers were effective in delaying the first crack appearance and in reducing the cracking tendency of the matrix at its plastic state. This happens due to the high elastic modulus of fibers compared to the cementitious matrix [4].

5.3 EFFECT OF LECHUGUILLA FIBERS ON PLASTIC SHRINKAGE

In a comparative study between PVA fibers and natural fibers(flax and Lechuguilla) in the mitigation of plastic shrinkage cracking, Lechuguilla fibers with a length of 40mm and a 0.7% volume faction , the total crack area, cumulative crack width, and widest crack observed were reduced by 93%, 89%, and 67%, respectively. The surface roughness of the Lechuguilla fibers increases its contact area with cementitious matrix, resulting in a similar strength as the one obtained for flax fibers. The addition of Lechuguilla fibers at 0.7% volume fraction resulted in the reduction of number of cracks appeared in the mortar [6].

5.4 EFFECT OF COCONUT FIBERS ON PLASTIC SHRINKAGE

Coir is a hard and stiff biodegradable lignocellulosic fibre obtained from the fibrous mesocarp of coconut fruits, accounting for around 25% of the nut. Coir fibres are strong, weather resistant, and somewhat waterproof due to their high lignin concentration, and they can be chemically changed. The fibres also have a high elongation at break, which means they can be stretched past their elastic limit without breaking. Coir fibres have many advantages, including low cost, high lignin content, low density, availability, strong elongation at break, and low elastic modulus. Coir fibres are mostly composed of lignin, hemicellulose, and cellulose. Coir fibres' average chemical composition ranges from 32 to 50 percent cellulose, 0.15–15 percent hemicellulose, 30–46 percent lignin, and 3–4 percent pectin. This emphasises the fact that cellulose and lignin are the two most abundant components of plant fibres. The variations in coir fibre characteristics can be related to the source of the coconut plant from which the fibres were extracted or the method of extraction used. Coir fibres have a density of 1.1–1.5 g/cm3, a young's modulus of 2–8 GPa, and a tensile strength of 105–593 MPa. 10–180 percent water absorption and 15–51 percent break elongation These qualities can vary depending on the fiber's origin, pre-treatment, and extraction processes [19]. A reduction in the restrained plastic shrinkage was observed with the addition of 0.5% coconut fiber of length 25mm in the study by Filho R. et al. The first crack appeared 90 min after placing the mix in the plain mortar specimen. Furthermore, two new cracks appeared after 95 and 145 min, while three cracks appeared in the coconut fiber reinforced composites after 180 min from casting. The crack widths in coconut fiber reinforced specimens are narrower than in plain mortar specimens [5]. The first crack appeared at 15 min in the control mix of foam concrete, whereas the times of occurrence of the first crack were 35, 25, and 27 min for the addition of coir at a volume fraction of 0.3%, 0.4%, and 0.5%, respectively. So, the addition of coir to the foam concrete resulted in the delay of the first crack appearance [9].

5.5 EFFECT OF ANIMAL FIBERS ON PLASTIC SHRINKAGE

Recycled pig hair could be a cost-effective alternative for improving the mechanical characteristics and durability of cement-based materials (CBM), while also helping to reduce environmental challenges associated with the global pork industry. In recent decades, the use of waste to replace components and/or improve the properties of CBM has intrigued the interest of researchers worldwide, and significant progress has been made by incorporating wastes such as recycled aggregates, plastic bottles, rubber tyres, glass, or fly ash into cement-based materials. The addition of fibres to CBM could provide cracking control at early ages and boost fracture toughness to varying degrees depending on matrix strength, fibre type, fibre modulus of elasticity, fibre aspect ratio, fibre orientation, and aggregate size. Pig hair is currently a large component of food industry waste. Animal fiber (pig hair) is a massive food industry waste which has shown good results in reducing plastic shrinkage cracking in mortars. Pig hair considerably reduced plastic shrinkage cracking, particularly at high fibre doses (8 kg/m3).The stiffness of the mortar at early ages increases with the addition of fibers and it redistribute water near the surface. These mechanisms are probably responsible for the reduction in plastic shrinkage cracking. The incorporation of pig hair decreases the crack width and delays the appearance of macroscopic cracks. The addition of pig hair consistently decreased the width of the crack as the fiber dosage increases up to 8 kg/m3 of mortar [1].

6. 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 natural fibers. Several test procedures for assessing restrained plastic shrinkage cracking of concrete are mentioned in this literature. Different crack measuring techniques are also discussed which are manual procedures, DIP (Digital Image Processing) and digital image correlation (DIC). The effect of different natural fibers on plastic shrinkage cracking in concrete is also discussed.

The addition of flax fibers in cement-based materials leads to the reduction in plastic shrinkage. This may be due to the hydrophilic nature of flax fibers and its superior quality in improving the tensile capacity of concrete. The increase in fibre content results in fewer concrete plastic shrinkage cracks. The inclusion of sisal fibers is effective in delaying first crack appearance which may be attributed to the high elastic modulus of fibers compared to the cementitious matrix, in addition to its ability to provide bridging forces across the cracks. Incorporation of Lechuguilla fibers at 0.7% volume fraction significantly reduced the total crack area, cumulative crack width and widest crack observed in the mortar. Coconut fibers were also effective in delaying the first crack appearance, decreasing the crack width etc. Animal fiber (pig hair) significantly prevented plastic shrinkage cracking, especially at high fibre doses (8 kg/m3).

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