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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Control of Restrained Plastic Shrinkage Cracking using Flax Fiber.

A Thesis in Structural Engineering

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ABSTRACT

Plastic shrinkage cracks are precursor for durability concerns in concrete. An understanding of the phenomenon will lead to diminishing this detriment in the future. The utilization of natural fibers from agricultural by-products like flax is a glamorous option to develop sustainable building materials in the construction industry. However, the extraction of flax fiber has not yet been explored in Ethiopia. Experimental investigation on the potential of low volume content and short flax fiber in resisting restrained plastic shrinkage cracking was performed. The research focused on assessing the performance of this natural fiber. Three volume fractions of flax fiber (0.0185%, 0.035%, and 0.055%) with a length of 25mm were compared with the plain restrained slab specimen exposed to an environmental chamber which induced high evaporation rate to promote the plastic shrinkage cracking. In order to enhance adhesion between the fiber and matrix, the surface of flax fiber was coated with cement grout. Image analysis technique was used to determine the crack width and length distribution using MATLAB functions and also a crack control efficiency was deliberated.

The research work outcome indicates that at a volume fraction of 0.035% total crack areas were reduced by 73% relative to plain specimens and multiple localized cracks of the average width reduced by 70% limited to less than 0.49 mm. Finally, an optimum fiber content was obtained at 0.055% which has practically eliminated the visually visible restrained plastic shrinkage cracking.

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This is to certify that the thesis prepared by Lidya Emmanuel, entitled: *Control of Restrained Plastic Shrinkage Cracking using Flax fiber* and submitted in partial fulfillment of the requirements for the degree of Master of Sciences in Civil Engineering (Structures) complies with the regulations of the university and meets the accepted standards with respect to originality and quality.

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Dedicated to my beloved parents,

Tadelech Djote and Emmanuel Guteta.

It's always my greatest motivation to make you proud.

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Notations and Acronyms

Notations:

CS= control slab

$FFRS_1$= flax fiber reinforced slab with 0.0185%

$FFRS_2$= flax fiber reinforced slab with 0.035%

$FFRS_3$= flax fiber reinforced slab with 0.055%

ER= evaporation rate ($kg/m^2/hr$)

T_c = concrete temperature, ^0C

T_a = air temperature, ^0C

RH= relative humidity (%)

V_f = volume fraction of fibers

Acronyms:

CRR= crack reduction ratio

ACI= American Concrete Institute

ASTM= American Society for Testing Materials

MATLAB= MATrix LABoratory

AAiT=Addis Ababa Institute of Technology

NRMCA= National Ready Mixed Concrete Association

1. Introduction

1.1 Background and motivation

It is proverbial that early-age cracking of cementitious materials plays a crucial role in regulating the long-term performance of structures. One of the most exasperating incidences when building with cementitious materials is the plastic shrinkage cracking. It is the earliest type of crack which occurs within the first few hours after placement while still in a plastic state and has not yet achieved any significant strength (Filho, et al., 2005). The phenomenon occurs especially during hot, windy and arid weather due to rapid and excessive moisture loss, mainly in form of water evaporation. When the rate of evaporation exceeds the rate of bleed water rising to the surface, the mixture will begin to shrink. (Kejin Wang, 2001). If this shrinkage is restrained in any way, tensile stress develops which tend to crack of the material, if it exceeds the tensile strength.

Plastic shrinkage cracks have been a severe problem for slab-like elements, even though they might be temporarily closed during surface finishing; they often propagate inwards and acts as weak points for pernicious agents which accelerates deterioration by infiltrating through the cracks, consequently leading to a reduction in durability, serviceability, and performance of structures. (Slowik, et al., 2008), (Slowik & Schmidt, 2010) (Sivakumar & Santhanam, 2006)

To prevent plastic shrinkage cracking, proper curing and covering the surface are among common external precautions. However, such practices are often not reliably followed. (Boshoff & Combrinck, 2009). Recently, natural fibers have received considerable attention as a replacement for synthetic fibers due to an increased emphasis on sustainability (Silva, et al., 2008) and their effectiveness in controlling plastic shrinkage cracking. Among them, Flax fiber rates the highest in terms of tensile strength, a property vital to the behavior of a crack inhibitor but an underutilized resource, (H.L.BOS, et al., 2002) (J.E.Ferbabdez, 2002) and often regarded as waste by-products of the agricultural process. Particularly, in most developing countries including Ethiopia; the straw from flax has been burned or discarded and used to bale hay by farmers. However, the fiber within the straw is one of the most durable and strong natural fiber making it an ideal candidate for an effective post-crack behavior. As stated by Ethiopian Institute of Agricultural

Research (EIAR), it has been estimated that an average of 150,000 hectares of flax waste is generated annually in the country. According to Boghossian & Wegner's study, the addition of low volume fraction of short flax fibers to Portland cement mortar is effective at 0.3% in reducing the cracks resulting from the restrained plastic shrinkage cracking under the condition that produces high evaporation rate (Boghossian & Wegner, 2008). Their experiment was undertaken on a specimen of substrate bases in order to provide uniform restraint. Though a standard testing method was introduced by ASTM C-1579 mainly for studying the influence of fibers on the plastic shrinkage cracking, it has created doubts to some researchers because of its incapability to induce cracking owing to insufficient restraint. (Sivakumar & Santhanam, 2006) , (Banthia & Gupta, 2009), (Boshhoff & Combrinck, 2013). Lately, Combrink modified the ASTM standard and proposed a new restrained testing mold for the pure plastic shrinkage cracking.

Hence, in this research work; attempts are made to experiment the characteristic of short and low volume flax fiber as a crack inhibitor material which could be an intermediate technological option to enhance durability and service life of cement-based structures. Besides, the thesis sets out to induce plastic shrinkage cracking using the recently proposed mold by Combrink (Steyl, 2016). Furthermore, a MATLAB script was written to discover the behavior of crack width and length under conditions that produce a high evaporation rate and also comparisons of three different fiber dosages were conducted with the plain mortar slab specimen.

1.2 Significance of the study

In most of the cases, plastic shrinkage leads to the appearance of surface cracking, in which structures become more prone to the ingress of aggressive agents that can cause deterioration in the short or long term, reducing the durability. Hence, it is necessary to propose the best alternative that eliminates this effect. In line with this, the outcome could create a boost for further investigation to ameliorate the quality of structures; especially by enhancing the durability. Accordingly, it will lay a foundation for the future "green cement" technology in the construction sector of Ethiopia.

1.3 Objectives of Research

The main objective of this research is to investigate the effect of a low volume fraction of short flax fiber on restrained plastic shrinkage cracking of cement mortar. In doing so, the research aims to achieve the following sub-objectives:

- Extraction of flax fiber from its straw.
- Mechanical characterization of flax fiber.
- Evaluate effects of different fiber volume fraction on plastic shrinkage cracking in a restrained slab specimen.

1.4 Scope

This research particularly investigated the capability of flax fiber in resisting the restrained plastic shrinkage cracking of mortar specimens using an Ordinary Portland Cement with water to cement ratio of 0.55. Fiber volume fractions of 0.0185%, 0.035% and 0.055% with lengths of 25mm were chosen for the exploration. However, due to unavailability of scanning electronic microscope (SEM) and X-ray diffraction (XRD); the study couldn't involve in the research work.

1.5 Organization

Chapter one provides a general introduction to the thesis with a brief content of the background information, and rationale for the study. Chapter two reviews the relevant literature on influencing factors of the plastic shrinkage, effect of fibers and the testing techniques of slab specimens. In Chapter three, the extraction procedure of flax fiber and surface treatment is described. Besides, the materials and methods used and their testing procedures are presented. Chapter 4 explains the results and discussions of the findings. Finally, Chapter 5 includes the conclusions and recommendations for future work.

2. Literature Review

2.1 General Introduction

Despite the fact that there is tremendous knowledge of mechanisms and precaution measures of plastic shrinkage cracking, the risk remains a serious concern for large surface area structural members. Many parameters may influence the cracking tendency at its early age. For instance: - w/c, cement type, fines content, member size, and ambient conditions. (Lura, et al., 2007), (Boshhoff & Combrinck, 2013). Among several methods investigated to reduce the risk of plastic shrinkage cracking such as mixture design, admixtures, fibers, secondary reinforcement, proper curing, and surface finishing methods; fiber reinforcement is one of the most effective ways. (Bentur & Mindess, 2007), (Kiani & Bakhshi, 2012) (Rahmani, et al., 2012). The use of natural, short and low volume fibers in mortar and concrete is increasing in recent years due to their effective performance. Above all, to improve sustainability in construction material usage; flax fiber becomes a marvelous option.

This chapter is devoted to providing the review of relevant literature on the influence of environmental conditions, the effect of fibers and testing techniques of slab specimen to evaluate plastic shrinkage cracking.

2.2 Influence of Environmental Conditions

According to (ACI 305, 1999) “Plastic shrinkage cracking is frequently associated with hot weather concreting in arid climates. It primarily occurs in flat work but also in beams and footings. In a similar way, it may develop in other climates whenever the evaporation rate is greater than the rate at which the water rises”. The environmental factors that can highly influence the water evaporation rate are the temperature of concrete, the temperature of the air, relative humidity and wind velocity (Uno, 1998). A graphical method to estimate evaporation rate is described in (ACI 305, 1999). The outcome of this nomograph is assumed to provide an indication of the possible onset of plastic shrinkage cracking.

To use these charts:

1. Enter with air temperature, move *up* to relative humidity.
2. Move *right* to concrete temperature.
3. Move *down* to wind velocity.
4. Move *left:* read approximate rate of evaporation.

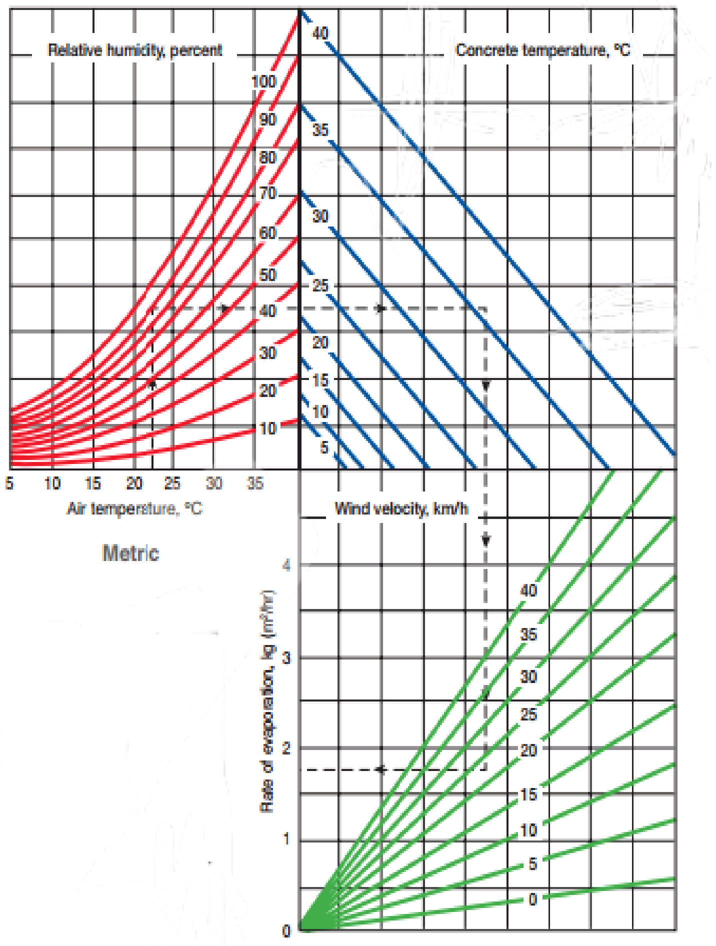


Figure 2-1 Nomograph for estimating water evaporation rate.

(H.Kosmatka, et al., 2002)

Since evaporation rate is considered as a probability indicator of plastic shrinkage cracking, the focus has been on this specific parameter in cement technology. Therefore, precautions must be taken if the water evaporation rate is equal to or more than 1.0 kg/m^2/hr. because the chance of crack occurring is high. (Bentz & Weiss, 2008). According to ACI method, commonly quoted values for normal concretes and silica fume containing concretes are 1kg/m^2/hr and 0.25 kg/m^2/hr respectively. Moreover, for the state New York and the city of Cincinnati, 0.75 and 0.5 kg/m^2/hr were recommended separately. Similarly, Canadian codes and Australian references recommended 0.75 and 0.5 kg/m^2/hr respectively. (ACI305R, 2010). The limit of 1kg/m^2/hr turns up to be conservative.

In 1998, Uno proposed a single operation equation to predict the water evaporation rate.

$$E=5([T_c+18]^{2.5}-r.\,[T_a+18]^{2.5})\,(V+4)*10^{-6} \qquad \text{Equation 2-1}$$

Where,

E= water evaporation rate, kg/m^2/hr.,
T_c= concrete temperature, ^{0}C,
T_a= air temperature, ^{0}C,
r= relative humidity, (%), and
V= wind velocity, km/hr.

The formula is very practical for on-site quick checks to see if evaporation is going to be a critical factor or not. (Sayahi, 2016) reported that the evaporation rate calculated by the formula and the one extracted from nomograph give almost similar evaporation rates. In contrast, (Manal Al-Fadhala, 2001) reviewed the accuracy of National Ready Mixed Concrete Association (NRMC) nomograph, and found that it reasonably represents the evaporation rates up to 0.5kg/m^2/hr. Above this, the nomograph tends to overestimate the rates of evaporation. This investigation had chosen UNO's equation to calculate the rate of evaporation quickly.

2.3 Testing Techniques of slab specimens

Different sizes, restraint magnitudes, and studies have been widely conducted by many researchers. Such as (Kraai, 1985), (Shaeles & Hover, 1988), (Cohen, et al., 1989), (Soroushian, et al., 1993) (Nanni, et al., 1993), (Berke & Dallaire, 1994), (Balaguru, 1994), (Banthia, et al., 1996), (Soroushian & Ravanbakhsh, 1998), (Banthia & Yan, 2000) (Mora-Ruachho, et al., 2008) (Ramakrishnan, 2001), (Wang & Shah, 2001) (Bayasi & McIntyre, 2002) (Trottier, et al., 2002), (Najim & Balaguru, 2002), (Qi, et al., 2005). Banthia et al [1996, 2000] suggested the use of specimens cast directly on a rough sub-base with exposed aggregates to imitate restraint in real structures. Modifications to Banthia's test method have been used by researchers.

In 2006, ASTM standard C1579 was introduced based on the riser type of substrate restraint test. The mold was mainly developed to compare the plastic shrinkage cracking behavior of different concrete mixtures containing fiber reinforcement under prescribed conditions of restraint. It should be noted that several tests performed by this testing specimen resulted in no cracking. To solve this case ten bolts were added to the two ends of the mold. (Sayahi, et al., 2017) This problem was also observed by other researchers such (Sivakumar & Santhanam, 2006) and (Boshhoff & Combrinck, 2013) where they had to modify the mold in order to increase the lateral restraint. After a decade, Combrink proposed a new restrained slab testing specimen (dog-boned shaped mold) as shown in fig 2-2, for the formation of pure plastic shrinkage cracking by considering the shortcoming of the ASTM standard. (Steyl, 2016)

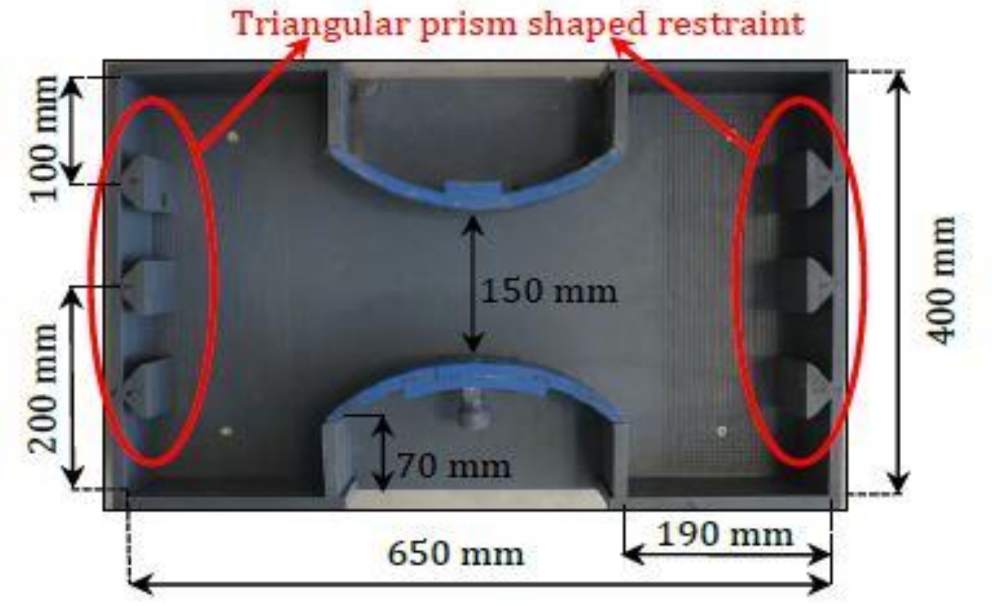


Figure 2-2 The Proposed mold (Steyl, 2016)

The test geometry provides sufficient restraint while complying with all the design requirements in ASTM C1579.

2.4 Effect of fibers on plastic shrinkage cracking

Many researchers have begun to focus on the effectiveness of natural fibers in controlling plastic shrinkage cracking. Low volumes of randomly distributed short fibers have been reported as one optimal solution to control plastic shrinkage cracking (Hannant, 1978) (Balaguru, 1994). Illustration of fibers bridging the crack to prevent further expansion by redistributing the stress concentration is shown in fig 2-3 (Folliard, et al., 2006)

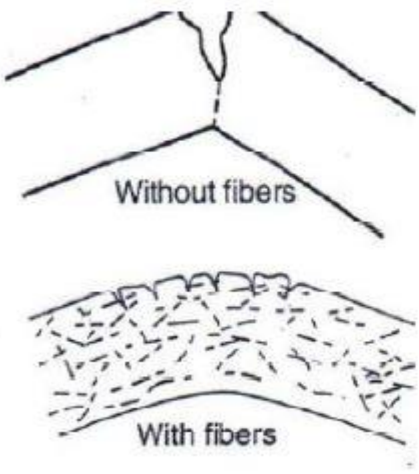


Figure 2-3 Effect of fibers on the failure mechanism (Folliard, et al., 2006)

To date, more and more experiments were conducted to show how fiber reinforcement can be used to mitigate cracking. Although limited research has been conducted dealing specifically with flax fiber, a research performed by (Boghossian & Wegner, 2008) found that flax fibers were more effective than other commercially available fibers in reducing plastic shrinkage cracking, decreasing the total crack area and maximum crack width by 99% relative to plain mortar at 0.3%, they believed the ability of fibers to reduce cracking must be attributed primarily to its capability to improve the tensile strength of fresh mortars and prevent cracks from growing. It is also reported that the improvement increases with increasing volume fraction. Similarly, Juarez indicated that flax fiber at 0.7% was effective in controlling restrained plastic shrinkage cracking which resulted in a reduction of 93% of the total cracking area compared with plain mortar specimens (C.A Juarez, 2015).

However, results mainly varied due to the different mix proportions obtained; in addition, due to the degree of restraints.at concrete substrate. Case with volume fraction of 0.7% showed a high content in water to cement ratio as well in fine aggregate with lower specific gravity of fiber (1.42). While when 0.3% volume dosage was investigated, a fiber specific gravity of 1.52 were used and 8% silica fume was incorporated in the cement. Both researchers used fibers without any surface preparation. And they quoted that, length of fiber seems to have no significant influence on total crack area; it only affects the workability of the mixture. According to Jurarez's study, a better fiber distribution was observed when short fibers were used in the mortar mix. (Romildo D. Toledo Filho, 2004) reported that the addition of 25 mm short sisal fibers at 0.2% by volume were effective in controlling plastic shrinkage cracking. Moreover, Cellulose fibers at 0.06% volume fraction (0.9 kg/m3) reduced plastic shrinkage crack area by 78%. (Soroushian & Ravanbakhsh, 1998) Besides, glass fiber showed a reduction of 97% in the crack area at 0.066% and cracks were completely eliminated at 0.1%. (Gupta, 2008).

Although previous researchers did a great job in highlighting the ability of flax fibers in reducing cracks induced by restrained plastic shrinkage; the investigation reported in literatures has been evidently small in number.

Even though the experiments mentioned earlier used flax fiber, a difference in property, volume content, substrate base usage and outcome was observed. Noticing the gap above, this research is the first attempt in Ethiopia to explore the potential of flax fiber; also, to discover whether the results would be similar with prior studies or not, which could serve as an additional data base and guideline of the country’s building code as well.

3. Experimental Investigation

3.1 Introduction

This chapter provides precise information on the materials and experimental methods used in the study. The experimental program was conducted at AAiT construction materials laboratory. Details of material composition, fiber preparation, testing procedures, and environmental conditions are presented.

Slab-specimen mold adopted from (Steyl, 2016) were used and samples were tested. Fresh fiber reinforced mortars with the same mix proportions of mortar making materials were cast subjected to hot, dry and windy conditions in an environmental chamber to promote cracking. A bunch of images was taken above the specimen and processed using MATLAB script developed to determine the crack area and also to demonstrate the mitigation of plastic shrinkage cracking by flax fiber.

The experimental strategy is described below using a flowchart. (fig. 3-1)

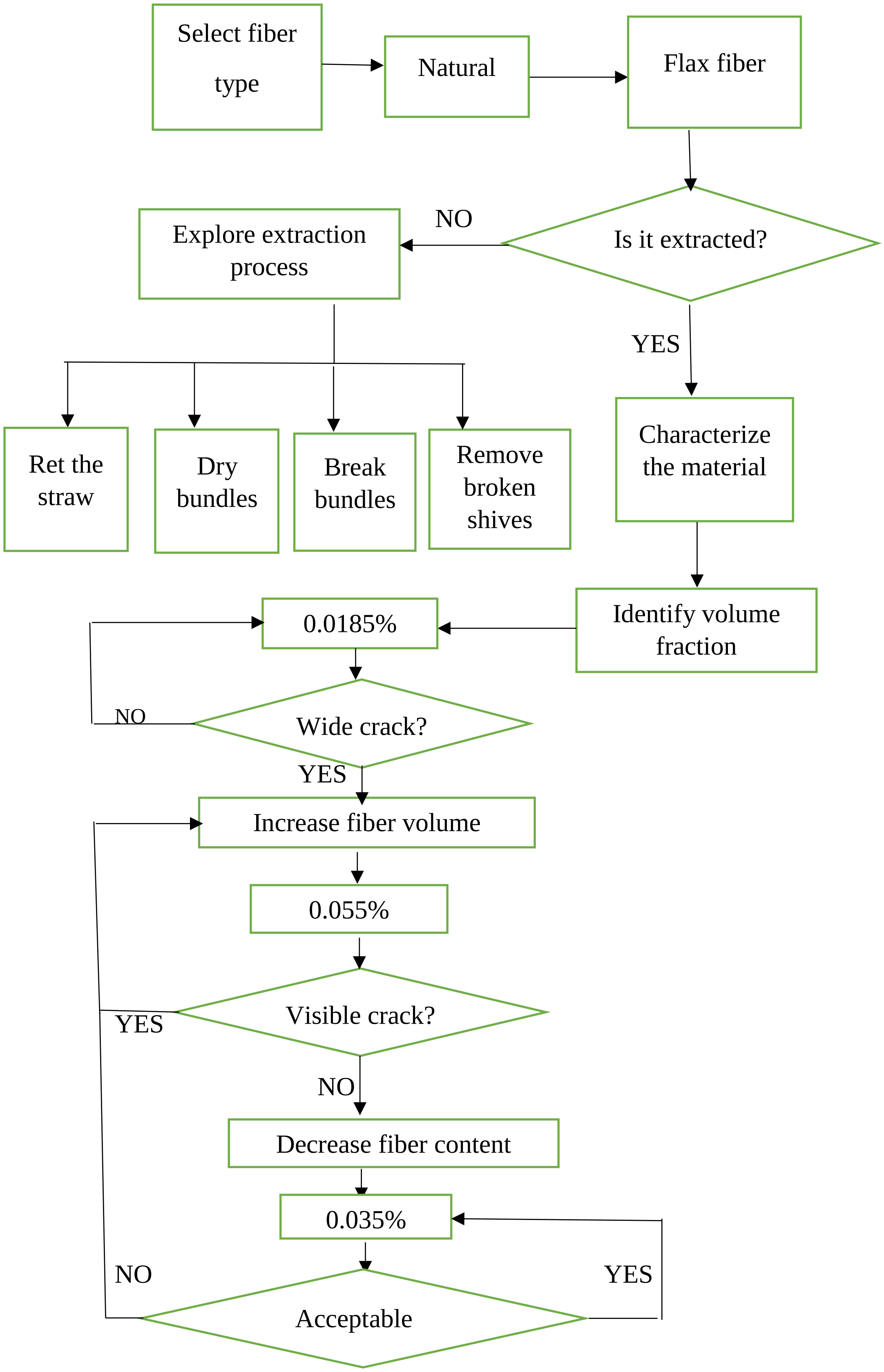


Figure 3-1 Flowchart for the Experimental Strategy

3.2 Materials and Methods

3.2.1 Mortar Ingredients

Mortar was used rather than concrete, in order to increase the potential for cracking and enhance the ability to compare the performance of different fiber contents with the plain.

3.2.1.1 Cement

The cement used in this study is an ordinary Portland from Dangote with CEM 42.5 R grade and relative density of 3.15g/cm$^{3.}$ Table 3-1 provides a summary of the cement composition and its properties.

Table 3-1 Chemical composition of cement (Geremew, 2017)

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3
66.32%	22.82%	5.41%	3.37%	1.46%	2.16%

3.2.1.2 Fine Aggregate

Locally available particles of round shaped sand with fineness modulus of 2.73 was used to make up the mortar. Figure 3-2 shows some physical tests of sand, also Table 3-2 Presents their properties.

Figure 3-2 Some Physical tests of fine aggregates

Table 3-2 Summary of results for the physical test of fine aggregates

Physical Tests	Results
Bulk Specific Gravity	2.4
SSD Specific Gravity	2.5
Apparent Specific Gravity	2.667
Absorption Capacity	4.167%
Moisture Content	3.09%
Loose Unit Weight	1,442.5 Kg/m^3
Silt Content	3.24%

Moreover, fig 3-3 indicates Sieve analysis of the aggregate which was conducted according to (ASTM C136, 2001).

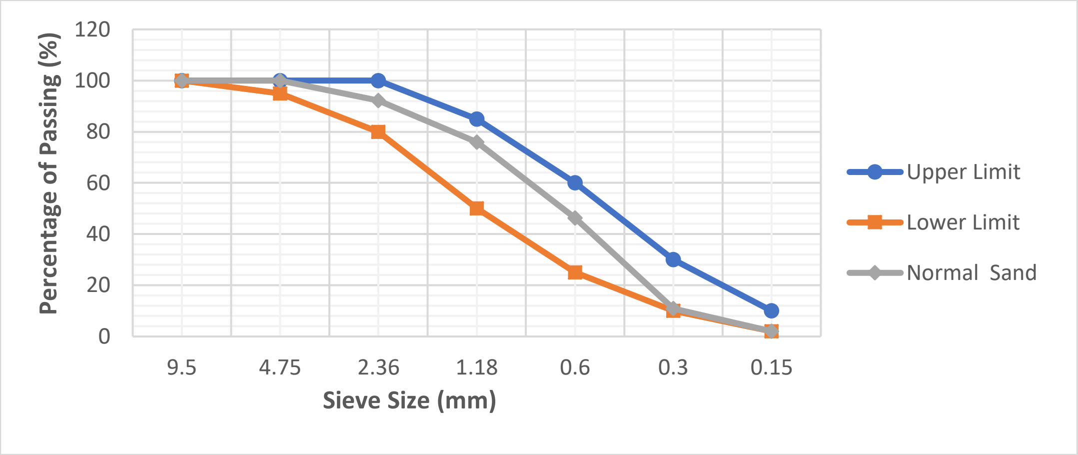


Figure 3-3 Gradation Curve for Fine Aggregate

3.2.1.3 Water

A tap water from the university compound was used to prepare all specimens in this study.

3.2.2 Flax fiber

The flax fiber used for this exploration was obtained by manually extracting them at the technology institute campus because processing technique is not yet adopted in the country. Bundles of flax grown in Oromia region with an average technical length of 80cm were collected from Holeta Agricultural research center. Fibers were decorticated, chopped to lengths of 25mm and 0.07mm diameter approximately.

3.2.2.1 Extraction Procedure

Process of extraction is of great importance since the quality, as well as the quantity of extracted fibers, are strongly influenced by the method of extraction employed. Extraction will separate fibers from the cementing substances such as pectin or lignin, wax, resin, fats, and other carbohydrates, in order to release the fiber completely from the stem. First, it had to undergo a process called retting. Since water retting or tank retting is known for producing more uniform and high-quality fiber (Nair, et al., 2013). The flax stem bundles kept in an open rectangular tank with a sufficient depth of water. Besides concrete cylinders and wooden plates were placed on top of the samples to keep them submerged. Right after the first few hours, color from the stems and dirt was blenched out resulting in light colored fiber. Then the water was replaced by fresh water so that fermentation can be more considerately controlled.

In this study, careful observation was taken daily to avoid too little or over retting process. When the retting is complete, the bundles became slimy and the inner woody parts were sprung while wrapped around a finger. At last, the method took 5-6 days to rot flax fiber properly.

Figure 3-4 Open tank retting of flax stems

After water retting is completed, the straw was taken out of the tank, bound in bundles (wigwamed) in a field. Wigwam consisted in setting up each wet bundle of retted straw with the butt ends resting on the ground and these spread out so as to allow free circulation of air (Robinson, 1940). Some bundles were very long which makes it difficult to set up in such a manner. Therefore, they were hanged-up to dry. The flax straw when wigwamed and hung required a few days of sunshine to dry.

Figure 3-5 Flax straw setup in Wigwams and hung up to dry

Breaking is the process that followed retting and drying in extracting the fiber from the stem. It consists essentially of breaking the woody portions of the straw into fine pieces, called shives. A manually operated four-legged metal device called a ‘breaker’ was employed for this purpose. See fig 3-6

It was accomplished by passing the retted and dried bundles of untied flax through fluted rollers gently to pound and crush the woody stem separating it from the fiber. This is repeated over the entire length of the flax stems until most of the brittle pith and cuticle gives away leaving the long band of fiber intact.

Figure 3-6 Breaking the flax steam by breaker

The last step completed the removal of the remaining broken stalk /shives and other non-fibrous parts by hand. Though this process was labor-intensive as well as time-consuming, it was worth to have a clean and long fiber as shown in fig 3-8.

Figure 3-7 Removal of flax shives manually

Figure 3-8 The extracted clean and long flax fiber

The fibers were chopped using a scissor to lengths of 25 mm and fiber contents by volume at 0.0185%, 0.035% & 0.055% were prepared for the experiment.

Figure 3-9 Chopped fiber length of 25mm

Since the diameter of flax fiber obtained for this research is very fine just like a hair; an accurate measurement was taken using a standard Micrometer screw gauge.

Figure 3-10 Fiber diameter measurement by Micrometer

3.2.2.2 Tensile strength test of flax fiber

Tensile properties of flax fiber have been determined using a Testometric universal testing machine equipped with 50 N capacity load cell. The sample length has been set to 225 mm and the cross-head displacement rate at 500mm/min.

Figure 3-11 Tensile strength test of flax fiber

For the reason that natural fibers are naturally available materials, variability on their strength was noticed depending on the matter of course, such as weather and soil conditions.

Table 3-3 summarizes the basic properties of flax fiber to easily understand their character.

Table 3-3 Characteristics of flax fiber

Fiber Type	**Length (mm)**	**Diameter (μm)**	**Relative Density (g/cm^3)**	**Tensile Strength (Mpa)**	**Elastic Modulus (Gpa)**
Flax	25	70	1.5	622 - 980	50 - 80

3.3 Experimental Procedure

3.3.1 Mix Constituents and proportion

All samples had the same components of mortar making materials; only the fiber dosage varied for the purpose of research. Table 3-4 indicates the ingredients and proportions obtained.

Table 3-4 Mix Proportions by mass

Content	**Kg/m^3**
Cement	594.2
Fine Aggregate	1,051.7
Water	324.4
FFRS$_1$	0.278
FFRS$_2$	0.525
FFRS$_3$	0.825

Flax fibers ready for surface treatment prior to mixing are shown in fig 3-12

Figure 3-12 Flax fiber ready for surface treatment

3.3.2 Preparation of Specimen

3.3.2.1 Specimen geometry

Specimen similar to those used by Combrink (Steyl, 2016) for restrained plastic shrinkage studies was adopted. The mold had a surface area of 650mm x 400mm and a depth of 100mm as shown in fig. 2-2 and 3-13. The use of three triangular shaped blocks on each side proved to be a practical solution to provide restraint while complying with all the mold design requirements (Steyl, 2016). It was covered with oiled polyethylene sheets in order to facilitate the de-molding process.

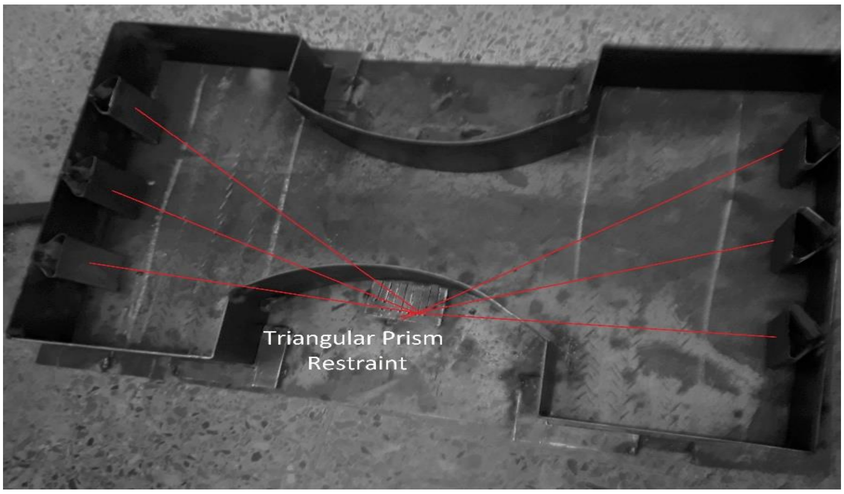


Figure 3-13 A mold with triangular prism restraint

3.3.2.2 Surface treatment of flax fiber

Flax fibers were coated with cement grout prepared with water cement ratio of one. The mineral substance is chosen due to its ability to resist in an alkaline environment and the aim of this treatment is to limit water absorption by a shielding effect against water. (Sawsen, et al., 2015). In addition, the economic aspect of preparing the grout found to be feasible than other chemical treatments in this study.

Figure 3-14 Flax fibers coated with cement grout

3.3.2.2 Test Procedure

The flow of fresh mortar was carried out first using a flow table apparatus and mold according to (ASTM C1437, 2007). Then Mortar together with the fibers was mixed using a hand mixing procedure in a 0.16 m3 pan mixer, to ensure that fibers were well distributed and randomly oriented. Thus, to prevent the balling effect. The laboratory condition was monitored for every mixture undertaken. Generally, the laboratory environment during mixing time had a temperature of 21±2 ° c and RH of 50±3.

According to (ACI 544, 2002), if low volume fraction of fibers is used; the wet mix is recommended. So, based on this fact, the mixing procedure used is presented below.

Fine aggregate and cement were first thoroughly mixed for about two minutes by hand until a uniform color and texture appeared, then water was added steadily at a constant rate while stirring and the mixing continued for a further couple minute. Afterward, ten grams of water sprinkled on the fiber surface to keep it moist. Then fibers were randomly distributed and stirred layer by layer to ensure a uniform dispersion throughout the mix for a period of 1-2 min depending on the fiber dosage. Subsequently, a hand shovel was used to fill the mold and vibrated on a vibrating table.

Immediately after casting, all mortar specimens were placed in the climate chamber which was switched on an hour prior to mixing in order to accelerate evaporation rate.

3.4 Environmental Conditions

3.4.1 Environmental Chamber

An environmental chamber was fabricated mainly to imitate an ideal condition for the formation of plastic shrinkage cracking. Nine halogen bulbs were set-up above the sample in order to simulate solar radiation and three electrical fans were placed in the environmental chamber to achieve a minimum wind velocity of 4.7m/s as specified in ASTM standard C1579-13. Several trial and error were required to achieve the desired state and rate of evaporation. See Appendix A.

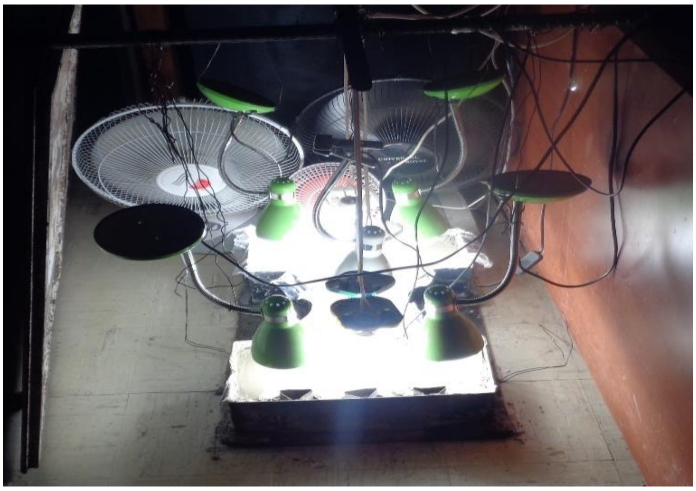


Figure 3-15 Side view of Environmental Chamber

Figure 3-16 Top view of Environmental Chamber

3.4.2 Restrained plastic shrinkage cracking test

The restrained slab specimens were transferred into the environmental chamber and ambient temperature was recorded every 30 minutes for 7 hours starting from the time of placement, and a series of images were taken so that crack measurement could be performed through image analysis.

3.4.2.1 Evaporation rate measurement

The method used to measure the evaporation rate is Uno's equation (equation 2-1). It enables to determine the rate from the ambient condition of the environmental chamber. Air temperature, relative humidity, and wind velocity were measured 10cm above the specimen surface using a Kestrel 3500 (pocket weather meter), as shown in fig. 3-17

Figure 3-17 Kestrel 3500 weather meter

Besides, a building electronic thermometer (JDC-2) with embedded cables was used to measure the temperature of a mortar. Fig 3-18

Figure 3-18 Electronic Thermometer

Readings were taken at 30-minute interval to observe the progress of the rate through time. Sample records during the test are presented in Appendix B.

3.5 Image Analysis Technique

3.5.1 Crack gauge

An attempt was done to measure the crack width manually by using BICS METHOD CRACK SCALE so as to be used in a comparison with the available edge detection method. However, the scale couldn’t read widths greater than 1.5 mm.

Figure 3-19 Manual measurements of crack width by Crack gauge card

3.5.2 MATLAB Script

The script was used to quantify the shrinkage cracking which consisted of three steps: -

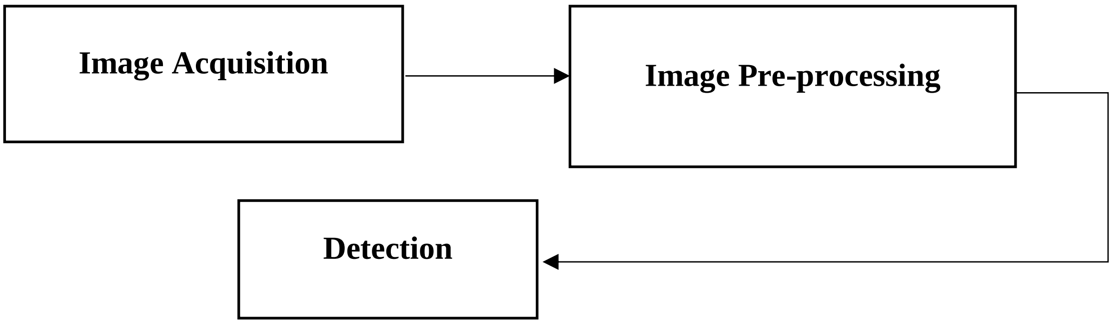


Figure 3-20 Image Analysis Procedure

All pictures were captured by 20.1 Mega Pixels resolution camera in a bright environment. Crack widths smaller than 0.35mm were not detectable.

The two main pre-processing steps applied in this research are the following.

- Colored to gray-scale conversion: - it is reasonable to assume that cracks don’t have any effect on the hue and saturation components. This is due to the fact that the cracks are a physical manifestation of the stresses in the mortar. Therefore, the digital images were converted to gray-scale.

- Image cropping: - it was found that removal of 10mm is sufficient to account for the influence of the side wall effect to avoid inaccuracies in the crack detection. In order to classify the edges detected by the edge detection algorithm as crack, the assumption that cracks are composed of thin interconnected is utilized. Once the cracks of interest are obtained, their width and the overall length were vital for assessment.

The following approach was used to classify a crack as a crack of interest.

- Connected regions in the binary edge detected image was constructed. To construct this, a flood-fill algorithm was used to label all pixels in a connected component containing pixel. The MATLAB function bwconncomp was used to obtain the connected regions. Finally, the crack was extracted as a black contour in a white background as indicated in the figures below.

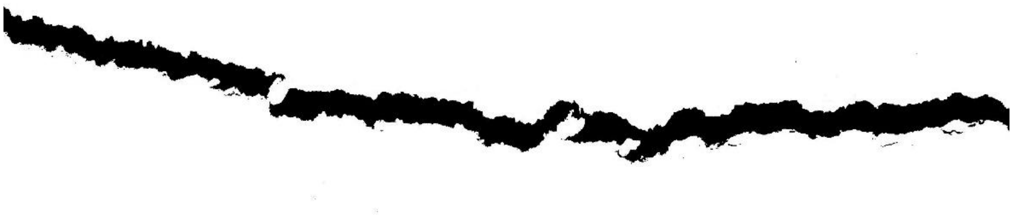


Figure 3-21 The final processed image of the plain specimen by MATLAB

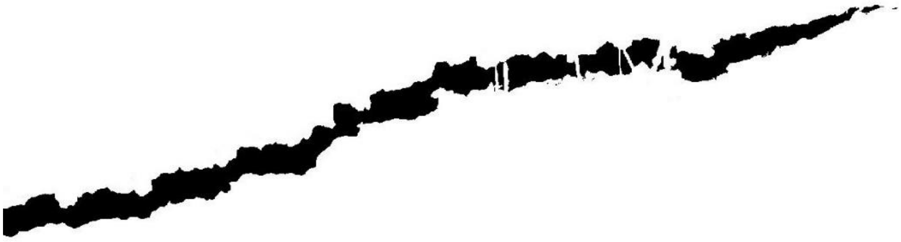


Figure 3-22 Portion of the 0.0185% length processed by MATLAB

Figure 3-23 The final processed image of 0.035% by MATLAB

The MATLAB script is presented in Appendix C.

4. Experimental Results and Discussion

4.1 Crack formation and Propagation

4.1.1 Crack initiation of 0%

An illustration of crack initiation and development characteristics for each mortar samples are shown in this section. The crack formation of plain mortar samples was sudden, happening very quickly till it reached the final length. Crack initiation of control specimens approximately started at a couple hours after the mortar was placed in the environmental chamber. The crack patterns encountered are discontinuous and random. Fig 4-1 shows crack formation process in one of the trial plain mortar samples. At the time to first crack, fine hairline cracks were observed for few seconds and continued to propagate through time.

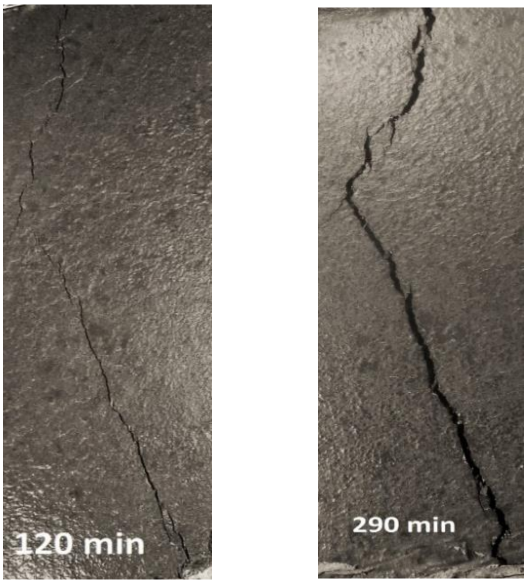


Figure 4-1 Initiation and Propagation of a trial control specimen

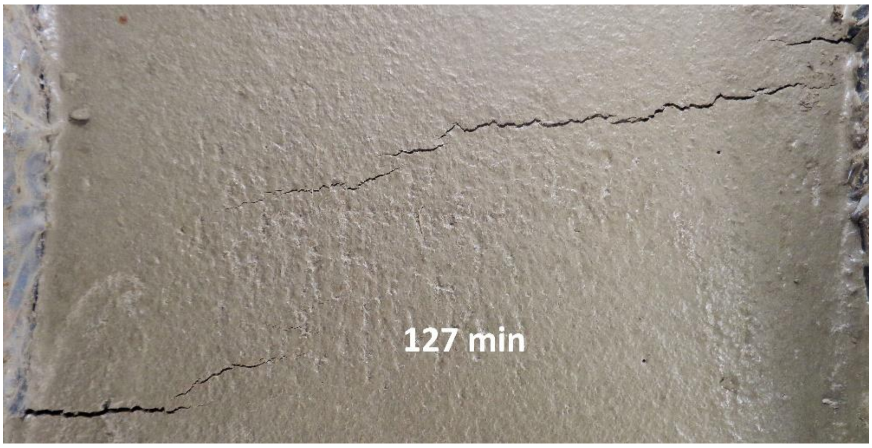
In addition, fig 4-2 indicates the main control mortar used in this study for comparison purpose, which had a different crack pattern but still discontinuous at initiation.

Regarding the crack width, the plain sample has widened through time till the hardening stage.

Figure 4-2 Crack initiation and growth in length of the main control specimen

4.1.2 Crack initiation of 0.0185%

The following images demonstrate a step by step formation of plastic shrinkage cracks in a varying volume fractions of flax fiber at 0.0185% right away from the initiation time till the final crack pattern is visible.



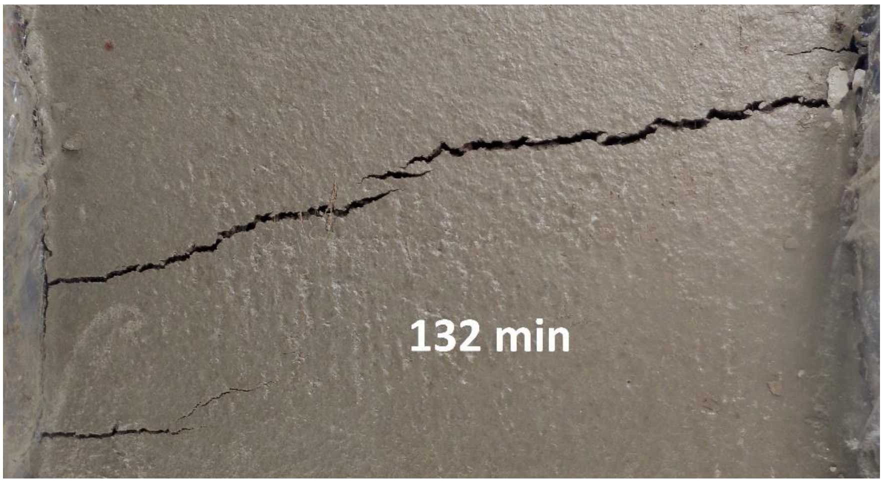


Figure 4-3 Crack initiation and growth in length at 0.0185%

Unlike the plain mortar, fiber reinforced specimens took a slower time to finalize the crack path. As shown in fig 4-3 an additional crack length was observed due to insufficient fiber content. The scenario is somewhat similar with the unstable equilibrium and also with the reinforced concrete having a small reinforcement ratio. If the fiber orientation angle in the mix was shifted a bit, the probability to arrest the crack might be very low. But fortunately, few fibers were able to bridge the cracks induced by restrained plastic shrinkage.

4.1.3 Crack initiation of 0.035%

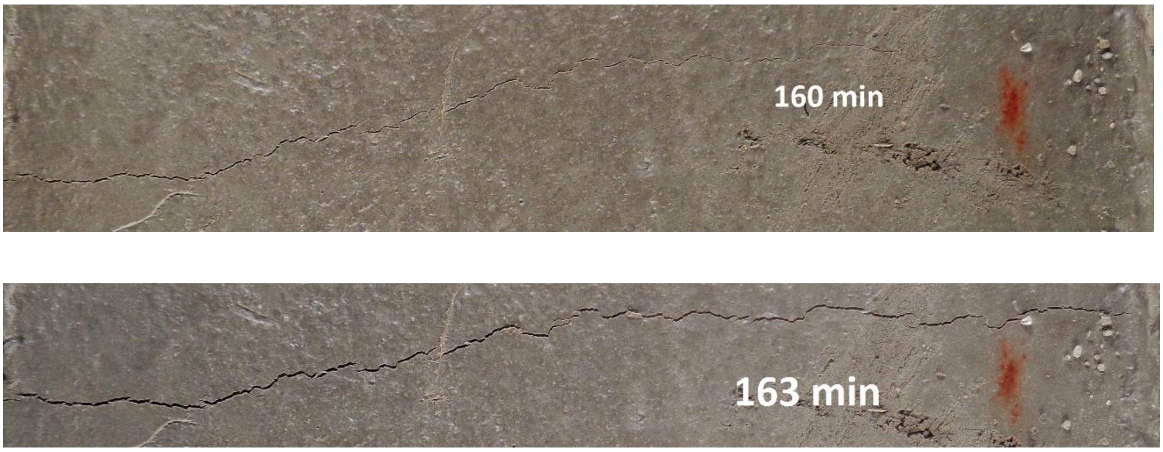


Figure 4-4 Crack initiation and growth in length at 0.035%

At 0.035% the width has already achieved approximately 75% of its final width earlier. The fibers transferred the stress to the internal micro-cracks to reduce the crack width at the early stage. As a result, due to an increased fiber dosage, larger cracks were refined into less harmful cracks. In this case, the situation can be considered as a stable equilibrium or as a mix having a much better reinforcement ratio than the previous. Hence, due to a larger number of fibers evenly distributed per unit volume in the mixture the possibility to arrest the crack has increased significantly.

4.1.4 The final propagated crack patterns

In this research, the final crack width mostly stabilized around the hardening time which is seven hours after casting. Figures below presents the final propagated crack widths at 420 mins of 0%, 0.0185% and 0.035% fiber volumes.

Figure 4-5 The propagated crack width of 0%

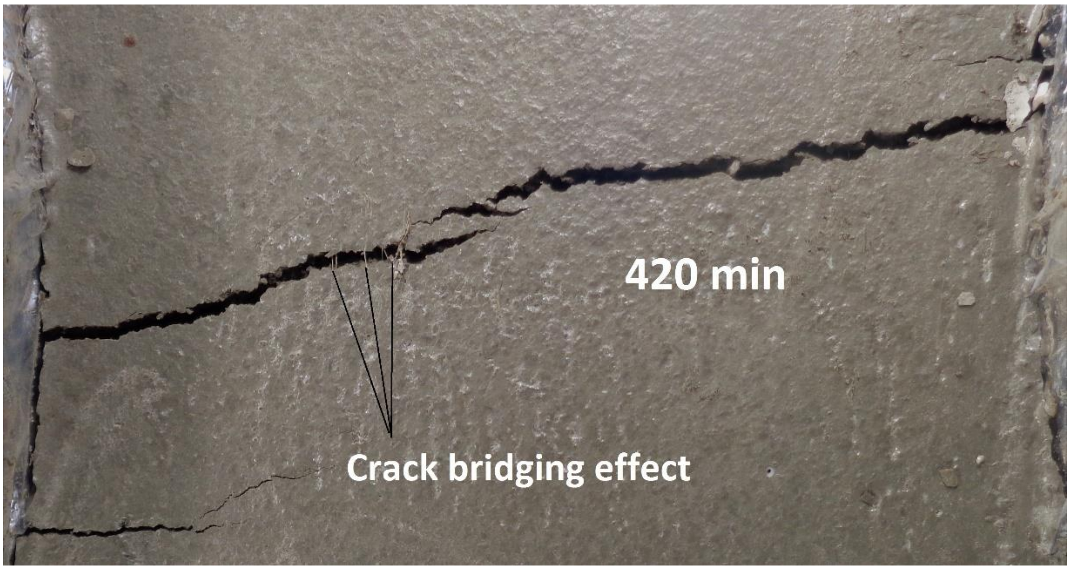


Figure 4-6 The propagated crack width of 0.0185%

Figure 4-7 The propagated crack width of 0.035%

The experiment clarifies the role of flax fiber in the mitigation of restrained plastic shrinkage cracking by lowering the possibility of tensile stresses exceeding the tensile capacity of the matrix and by reducing the overall shrinkage strains. In addition, fibers have a significant effect on impeding the growth by bridging the cracks.

4.2 Post – Cracking performance of flax fiber

4.2.1 Crack attribution

Quantified crack characteristics for restrained plastic shrinkage cracking test of the volume fractions are presented in table 4-1

Table 4-1 Results of restrained plastic shrinkage cracking test

Mix Designation	**Fiber Volume Fraction (%)**	**Maximum Crack width(mm)**	**Average crack width (mm)**	**Total Crack area (mm^2)**
CS	0	4.53	1.627	341.001
$FFRS_1$	0.0185	3.45	1.362	255.621
$FFRS_2$	0.035	0.951	0.493	93.5
$FFRS_3$	0.055	No visible crack	No visible crack	No visible crack

According to the recommendation of ASTM (C1579-13, 2013), the average crack width of the control panel has to be to the nearest 0.5mm and if the measurement is less than this number the test is regarded as invalid. Therefore, increasing the evaporation rate is suggested as an option to achieve this minimal average crack width. From the results above, it is clear that this research has attained the basic requirement of crack measurement.

Since fiber dosages of 0.0185%, 0.035%, and 0.055% were being compared with the control specimen (0%), the comparison graphs are plotted (fig. 4-8 and 4-9) for the crack width and area against fiber volume fraction using table 4-1.

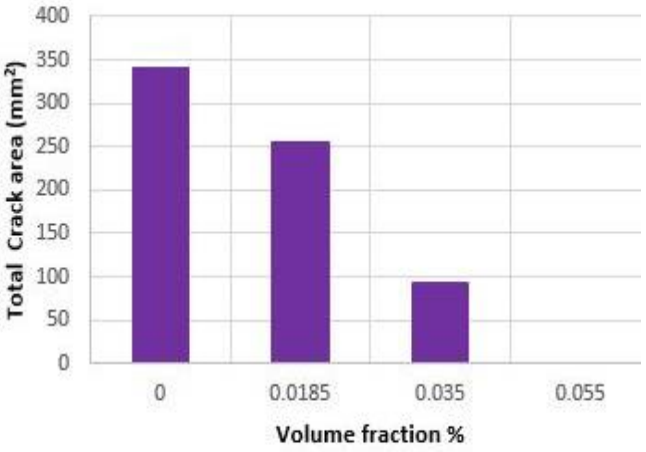


Figure 4-8 Total Crack area Vs Volume fraction

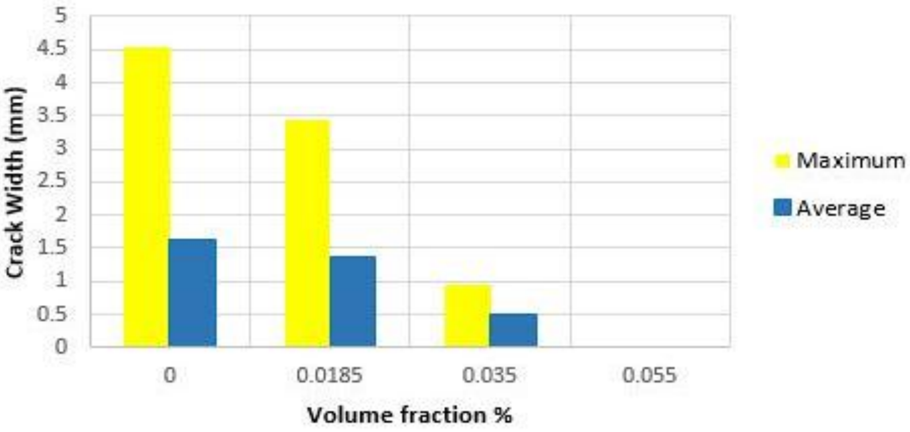


Figure 4-9 Crack width Vs Volume fraction

4.2.2 Crack control efficiency

Based on the findings, a crack control efficiency graph is presented and the values are included in table 4-2 for both the crack width and area using the crack reduction ratio (CRR) equations (equation 4-1 and 4-2) as outlined in ASTM (C1579-13, 2013). As it’s known, the average crack width reflects the overall crack width on the surface of the specimen. Whereas, the maximum crack width is useful while evaluating a structure for serviceability and durability. Fig 4-8 and 4-9 indicates a steady decrease in crack area as well as in crack width, with an increase in fiber volume fraction.

$$CRR = 1 - \frac{Average\ Crack\ Width\ of\ Fiber\ Reinforced\ Mortar\ Mixture}{Average\ Crack\ Width\ of\ Control\ Mortar\ Mixture} \qquad \textit{Equation 4-1}$$

$$C\mathrm{RR} = 1 - \frac{\text{Total crack area of Fiber Reinforced Mortar Mixture}}{\text{Total crack area of Control Mortar Mixture}} \qquad \textit{Equation 4-2}$$

These results tie well with previous studies (Boshoff & Combrinck, 2009) which highlighted the effectiveness of flax fiber in controlling plastic shrinkage cracking and reducing the total crack area and crack width. In addition (Banthia & Gupta, 2009) showed that the more the fiber content, the greater the crack-resistance of mortar.

Table 4-2 Results of Crack Reduction Ratio (CRR)

Mix Designation	**Fiber Volume Fraction (%)**	**Total Crack Area control Efficiency (%)**	**Maximum Crack Width Control Efficiency(%)**	**Average Crack Width control Efficiency (%)**
$FFRS_1$	0.0185	25	23.8	16.3
$FFRS_2$	0.035	73	79	70
$FFRS_3$	0.055	100	100	100

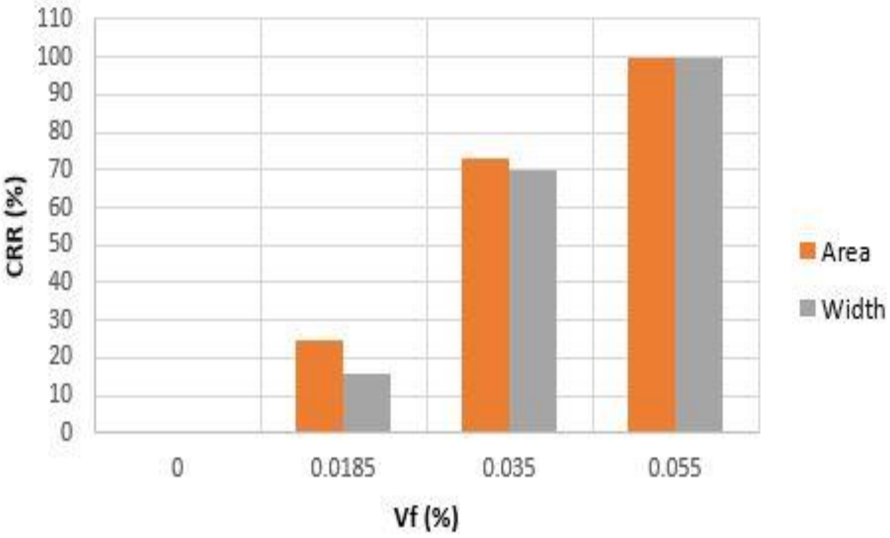


Figure 4-10 Crack Control Efficiency graph

The result provides evidence that flax fiber was ultra-efficient in the crack area and crack width control at 0.055% fiber volume. Moreover, Fibers at 0.0185% had a crack area and crack width control efficiencies of 25% and 16.3% respectively. Similarly, 0.035% was more effective with area and width control efficiency of 73% and 70% respectively with the crack width limited to less than 0.493 mm. So, a fiber volume of 0.055% (0.825kg/m^3) is found to be the optimal dosage in resisting the restrained plastic shrinkage cracking. In line with the previous study by Gupta, a reduction of 97% in crack area was observed at 0.066% volume fraction of mortar mixes and cracks were completely eliminated at 0.1% fiber dosage using a glass fiber. (Gupta, 2008)

Therefore, this data substantiates the competence of such natural fibers with that of synthetic by resulting a much better performance in crack resistance of the restrained plastic shrinkage.

4.2.3 Crack geometry distribution

Another novel finding of this research was the relation of crack length and crack width determination for every cement mortar specimen. Fig 4-11 illustrates the crack length observed on the control slab against the crack width.

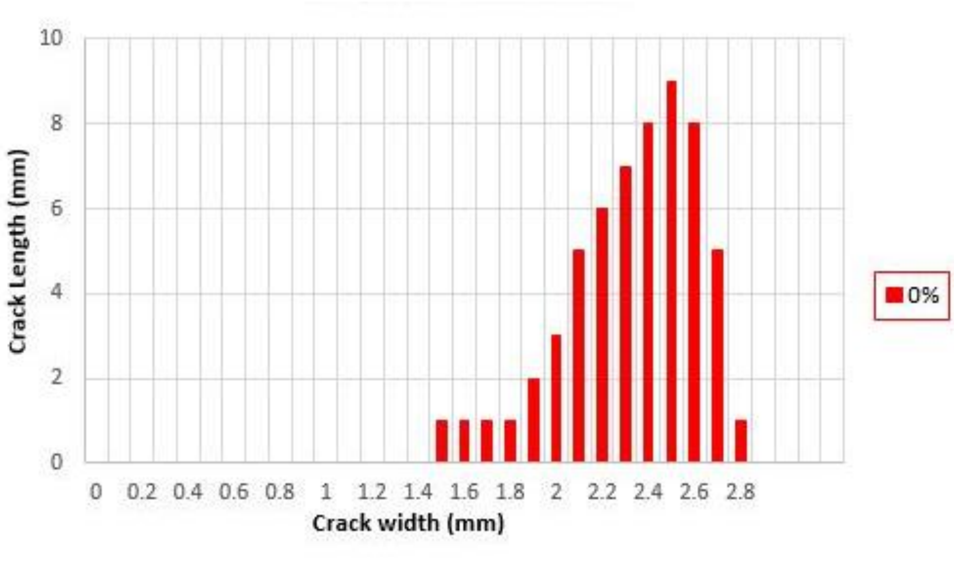


Figure 4-11 Crack geometry distribution of 0%

Results indicate that larger crack widths were encountered majorly owing to the critical tensile capacity of fresh mortar. Since there is no fiber addition in the mixture, tensile stresses had exceeded the tensile strength of the matrix leading to a wider crack width till the final setting time. Thus, crack widths were increased dramatically when the fiber dosage was null.

Unlike the plain specimen, fig 4-12 showed somewhat a different character of FFRS$_1$ sample which had two fine cracks and one thick crack at the middle as illustrated earlier in fig 4-6.

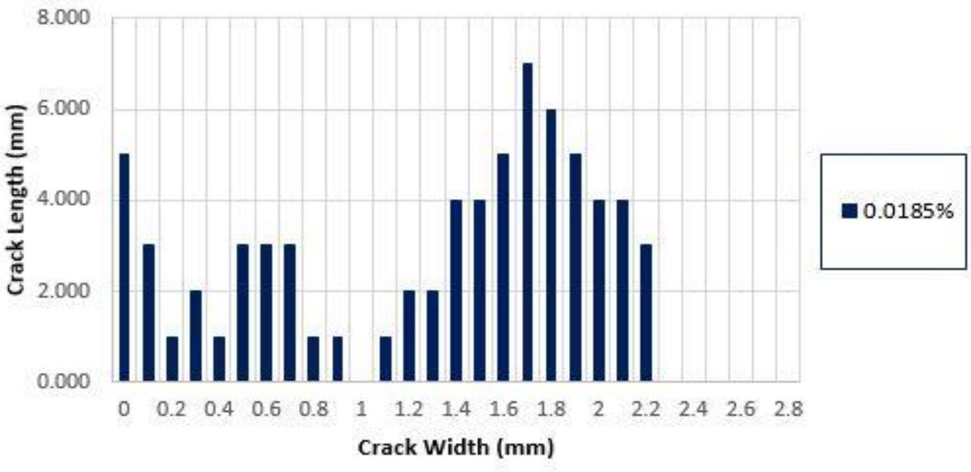


Figure 4-12 Crack geometry distribution of 0.0185%

Due to a very little amount of fiber dosage incorporation, the mechanism is complicated and arduous to generalize. The histogram represents behavior of the three cracks observed; though there is no significant effect on crack width reduction, only 16.3% average crack width reduction was noticed.

Besides, a crack histogram of 0.035% is indicated in fig 4-13.

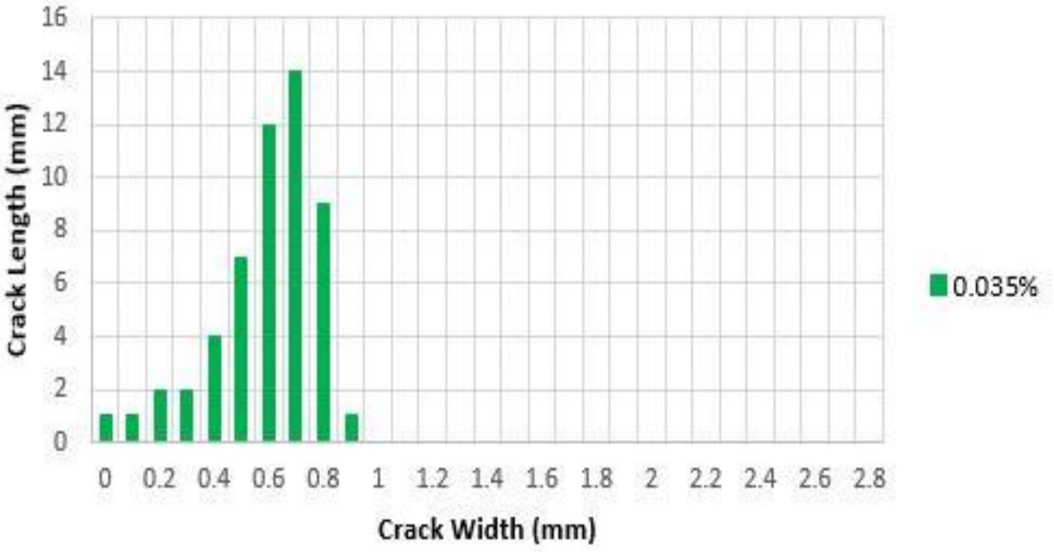


Figure 4-13 Crack geometry distribution of 0.035%

In this case, a meaningful reduction in crack width was achieved owing to the tensile strength of flax fiber which inhibited the growth of macrocracks. Here, crack widths are decreased as the fiber dosage increased resulting an inverse relationship.

Fig 4-14 illustrates the three crack histograms above in a graph so as to clearly understand the potential of flax fiber as crack inhibitor material.

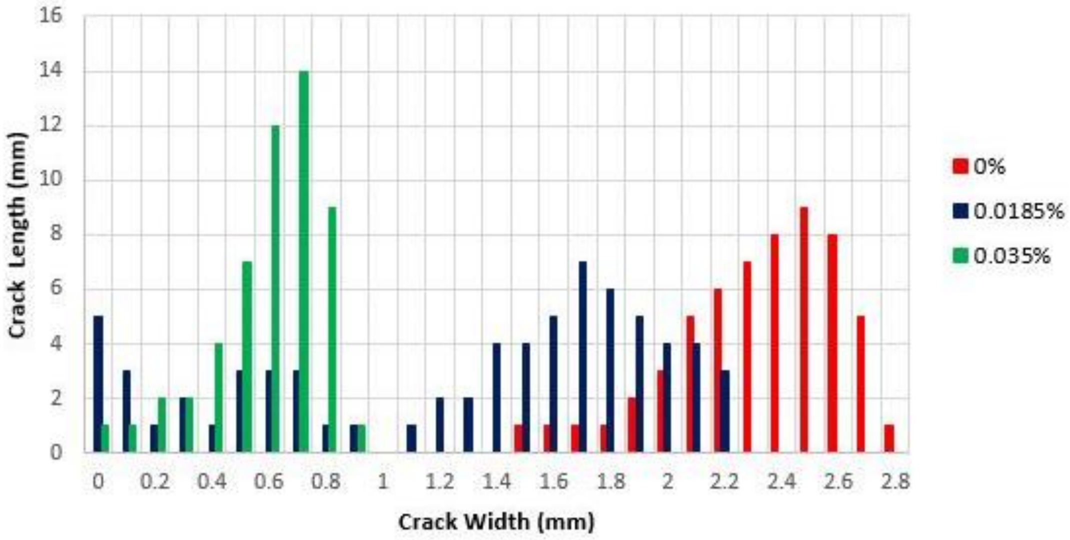


Figure 4-14 The total crack geometry distribution

Generally, the presence of flax fiber has dramatically reduced both the crack length and width of plastic shrinkage by providing bridging forces across cracks and thus prevent them from growing and propagating. It was found that the fiber dosage of 0.055% volume fraction to be the optimum percentage by arresting the crack and restrain their growth in mortar mixtures.

In spite of the fact that the mortar must crack first before the fiber starts to function properly, it is possible to incorporate and evenly distribute the flax fiber to amend the tensile capacity of the matrix.

5. Conclusions and Recommendations

5.1 Conclusions

The research work has investigated the influence of flax fiber inclusion to improve the cracking behavior of restrained plastic shrinkage. Their effects were evaluated by crack areas computed in MATLAB analysis. On the basis of the outcome, the following conclusions are deduced: -

- Flax fibrous mortar can offer result of inhibiting the restrained plastic shrinkage cracks.
- Distribution of crack length and width is highly affected by the fiber volume fraction.
- Addition of low volume content does not affect the workability of short flax fiber reinforced mortar specimen.
- The ultimate crack resistance performance of flax fiber is found at a volume dosage of 0.055% creating a ‘crack-free’ slab.
- The use of flax fiber could offer additional asset like, waste reduction and resource conservation.

The findings proved a promising capability of flax fiber in enhancing the restrained plastic shrinkage cracking performance, which could be applicable in the future construction sector.

5.2 Recommendations

Although, the results acquired from the research suggested a promising indication in terms of crack arrest; further investigation should be contemplated in concrete specimens under different environmental loads in order to recommend and validate the practicability of flax fiber. Since, the importance of the fiber is experimentally proved to mitigate the cracking; due attention has to be given not to burn or waste the by-product. Moreover, as the extraction process of the fiber is tedious, it has to be modernized and include mechanical processing for large quantities production.

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Appendix A

Trial and error setups to achieve the desired state.

12 04 2018

Appendix B

Sample records of evaporation rate during the test.

Time (min)	**RH (%)**	**Ta (^{0}C)**	**V (km/hr.)**	**Tc (^{0}C)**	**E (kg/m^2/hr.)**
30.00	36.3	29.1	18.2	23.6	0.626
60.00	37.8	29.7	18.2	24.7	0.663
90.00	32.6	33.2	18.2	26	0.747
120.00	32.5	34.4	18.2	27.4	0.825
150.00	36.4	31.5	18.3	28.4	0.936
180.00	32.2	34.5	18.3	29	0.972
210.00	32.4	30.3	18.3	30.4	1.231
240.00	32.9	32.1	18.9	31.7	1.325
270.00	36.2	32.7	18.9	32.8	1.347
300.00	38.6	31.2	18.9	34.5	1.536
330.00	34.6	30.5	18.9	36.4	1.850
360.00	32.6	34.1	18.9	39.5	2.139
390.00	32.2	35.1	18.9	43	2.570
420.00	34.2	36.3	18.9	46.9	3.034

Appendix C

The MATLAB script developed to determine the crack area is presented below.

```
function [ y, cc, clen ] = concretecrack( xrgb, N )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here


x=rgb2gray(xrgb);
clear xrgb;
%imshow(x);
%x=medfilt2(x);
%x=histeq(x);
%figure;imshow(x)
m=size(x);
% for i=1:m(1)
%     for j=1:m(2)
%         if (x(i,j)> 60)
%             x(i,j)=200;
%         else x(i,j)= 30;
%         end
%     end
% end
% figure;imshow(x);
y=edge(x,'sobel');
%figure;imshow(y)
clear x;
%imshow(y);
%s=size(y);
%N=5;
%figure; imshow(y)
%y=medfilt2(y);
%figure; imshow(y)
```

```
% xm3=medfilt2(x);
% ym3=edge(xm3);
% figure; imshow(ym3)
% xm5=medfilt2(x, [5 5]);
% ym5=edge(xm5);
% figure; imshow(ym5)
% xh=histeq(x);
% imshow(xh)
% yh=edge(xh);figure;imshow(yh)
% yhm=medfilt2(yh);

% figure; imshow(yhm)
CC = bwconncomp(y,8);
numPixels = cellfun(@numel,CC.PixelIdxList);
%[smallest,idx] = max(numPixels);
j=1;
idx(CC.NumObjects)=0;
for i=1:length(numPixels)
    if numPixels(i) < 8
        idx(j)=i;
        j=j+1;
    end
end
for i=1:j-1
    y(CC.PixelIdxList{idx(i)}) = 0;
end

%figure;imshow(y)
clear CC;
clear numPixels;
clear idx;
%figure;imshow(y)
```

```
% ych=medfilt2(y);
% figure
% imshow(ych)
dim = crackdim(y, N);
figure;imshow(dim);
cc = crackcolorcode(dim);
figure;imshow(cc);
clen = cracklength(dim,N);
end

function [ cc ] = crackcolorcode( dim )
%crackcolorcode color codes the cracks of different dimenstions
%   Detailed explanation goes here
%           1 - Green
%           2 - Cyan
%           3 - Yellow
%           4 - Magenta
%           5 - Red
    s=size(dim);
    cc=zeros(s(1),s(2),3);
    for i=1:s(1)
        for j=1:s(2)
            if dim(i,j)==1
                cc(i,j,2)=255;
            elseif dim(i,j)==2
                cc(i,j,2)=255;
                cc(i,j,3)=255;
            elseif dim(i,j)==3
                cc(i,j,1)=255;
                cc(i,j,2)=255;
            elseif dim(i,j)==4
                cc(i,j,1)=255;
```

```
            cc(i,j,3)=255;
        elseif dim(i,j)==5
            cc(i,j,1)=255;
        end
    end
  end
end

function [ dim ] = crackdim( y, N )
%dim calculates the pixel dimension of the cracks
%   Detailed explanation goes here
s=size(y);
dim=zeros(s(1),s(2));
for i=N+1:s(1)-N-1
  for j=N+1:s(2)-N-1
    if y(i,j)==1
        if (y(i,j+1)==1)
            for k=2:N
                if y(i-k,j)==1
                  dim(i,j)=k-1;
                  break;
                end
            end
        elseif (y(i+1,j)==1)
            for k=2:N
                if y(i,j-k)==1
                  dim(i,j)=k-1;
                  break;
                end
            end
        elseif (y(i+1,j+1)==1)
            for k=2:N
```

```
                    if y(i-k,j+k)==1
                        dim(i,j)=k-1;
                        break;
                    end
                end
            elseif (y(i+1,j-1)==1)
                for k=2:N
                    if y(i+k,j+k)==1
                        dim(i,j)=k-1;
                        break;
                    end
                end
            end
        end
    end
end
end

function [ clen ] = cracklength( dim, N )
%UNTITLED3 Summary of this function goes here
%   Detailed explanation goes here
s=size(dim);
clen=zeros(N,1);
    for i=1:s(1)
        for j=1:s(2)
             if dim(i,j)> 0
                clen(dim(i,j))=clen(dim(i,j))+1;
%               elseif dim(i,j)==2
%                   clen(2)=clen(2)+1;
%               elseif dim(i,j)==3
%                   clen(3)=clen(3)+1;
%               elseif dim(i,j)==4
```

```
%                 clen(4)=clen(4)+1;
%             elseif dim(i,j)>=5
%                 clen(5)=clen(5)+1;
            end
        end
    end
end
```

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