KYAMBOGO UNIVERSITY

FACULTY OF ENGINEERING
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

MASTER OF SCIENCE IN STRUCTURAL ENGINEERING

EFFECT OF BANANA FIBRES ON THE MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF CONCRETE

BY

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Declaration

This dissertation submitted to Kyambogo university graduate school; has not been accepted for any degree and is not concurrently submitted in candidature for any degree. It is the result of independent work, under the direct supervision from Kyambogo University. except where otherwise stated. Other sources are acknowledged by explicit references.

Signature.................. Date 20/08/2021

Karubanga Adolph

Abstract

This research presents an experimental study on the "Effect of Banana fibres on the mechanical and microstructural properties of concrete". Concrete being a quasi-brittle material, exhibits limited ability to restrict and reduce the generation and development of cracks. Recently, Natural fibres with their principal raw materials being agricultural wastes were found to be one of the suitable alternative cementitious reinforcing material. The main objective of this research was to study the effect of Banana fibres on the mechanical and microstructural properties of concrete; and the specific focus was four-fold: Properties of banana fibres; properties of plain and Banana fibre reinforced concrete (BFRC) in hardened state; and finally, behaviour of fibres in concrete. A total of 288 samples (cubes, beams and cylinders) of C20/25 concrete mix comprising of six (06) mixes for plain concrete (reference concrete) and BFRC, were cast and tested in the laboratory at 14 and 28 days and the behaviour of fibres in concrete modelled using ABAQUS computer software. BFRC had two parameters that were varied; fibre length (40 mm, 50 mm and 60 mm) and fibre content (0.00%, 0.10%, 0.25%, 1.00%, 1.50%, and 2.50%). Findings revealed the following; the tensile strength of banana fibres was 167.89MPa; samples containing banana fibres significantly impacted on the flexural and compressive strengths of concrete by 10 % and 13 % respectively; while a residual strength of up to 40 % for BFRC was obtained. The optimum fibre length was 40, and a lower fibre content of up to 0.25 % dosage. Further, samples containing fibres improved the microstructure of concrete; evidenced by a reduction in the interfacial transition zone of concrete (ITZ); no micro-cracks; cement paste deposited on surfaces of fibres and finally exhibited higher intensity than plain concrete. ABAQUS FEM predictions on the representative volume element (RVE) model using experimental test results revealed that samples containing fibres were able to resist failure compared to plain concrete for both tension and compression failure conditions. It was therefore concluded that the incorporation of Banana fibres in concrete was found to improve on concrete properties at lower fibre content and fibre length.

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Staff of Busitema University including, Mr. Godias Tumusiime laboratory Technician and Mr. Avutia Amos, from the Estates Department.

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My beloved parent, relatives and friends in my village for their support during the manual Extraction of the fibres, and for being a constant source of happiness, inspiration, and encouragement.

Dedication

I dedicate this dissertation to the almighty God for according me energy and zeal to tirelessly review a series of literature that has enabled me reach this great milestone.

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List of Acronyms

ACI	American Concrete Institute
ASTM	American Standard For Testing Of Materials
BFRC	Banana Fibre Reinforced Concrete
BSE	Backscattered Electron
BSI	British Standard Institution
COV	Coefficient of Variation
EDS	Energy Dispersive Spectroscopy
FEM	Finite Element Method
FM	Fineness Modulus
FRC	Fibre Reinforced Concrete
GF	Gram Force
GFRC	Glass Reinforced Concrete
ITZ	Interfacial Transition Zone
KHPP	Karuma Hydropower Project
MPa	Mega Pascal
NaOH	Sodium Hydroxide
RVE	Representative Volume Element
SD	Standard Deviation
SE	Secondary Electron
SEM	Scanning Electron Microscope
UTM	Universal Testing Machine
VPSEM	Variable Pressure Scanning Electron Microscope
W/C	Water to Cement Ratio
XRD	X-ray Difractometer

CHAPTER- 1 : INTRODUCTION

1.1 Background

Concrete has been used in the construction of Civil Engineering structures like buildings, dams and power stations, roads, bridges and tunnel linings; because of durability performance characteristics, strength under compression and availability of its principal ingredients that are less expensive compared to steel and other materials (Ravi *et al.*, 2015; Zhang *et al.*, 2018).

Concrete being stronger in compression can only resist compressive stresses but does not accommodate large tensile or flexural stress-induced deformations; the induced stresses lead to opening and propagation of cracks in concrete (ACI 207.2R-95, 2002; Neville, 2011). Cracking has adverse effects on the strength and durability performance of concrete due to exposure to ingress of deleterious chemicals and water (ACI 224R-01, 2001). This creates a necessity of reviewing existing approaches and come-up with innovations that could improve concrete properties (Mobasher, 2012).

The latest advanced resilient construction material that has proved to improve concrete properties is the incorporation of fibres and their performance has been linked to [Anti-cracking, Reinforcement & Toughness) (ACI 544.4R-18, 2018). According, to ASTM C1116, there are 4 types of fibres (ASTM C1116/C1116M-10a, 2015).

Recently, Natural fibres with their principal raw materials being agricultural wastes were found to be one of the suitable alternative cementitious reinforcing material. Because of being an agricultural waste, often left to rot in plantations, being environmentally friendly, readily available, cheap, and with good strength properties; has demonstrated enormous opportunities to the construction industry and our farmers. Regrettably; application of these fibres as reinforcing material in concrete is still Limited; hence requiring further investigations (Zhang *et al.,* 2018; Ahmad *et al.,* 2019).. Therefore, the principal focus of this research was on the utilization of Banana fibres as a reinforcement for concrete.

1.2 Problem Statement

Many civil engineering structures like bridges, buildings and dams, have been constructed while using concrete because it is strong under compression and its ingredients are readily available (Ravi *et al.,* 2015; Zhang *et al.*, 2018). Conversely, concrete being a quasi-brittle material, exhibits limited ability to restrict and reduce the generation and development of cracks (ACI 207.2R-95, 2002; Neville, 2011). Cracking exposes concrete to ingress of deleterious chemicals and water which interferes with its strength and durability, resulting into premature failure (ACI 224R-01, 2001); hence the need to improve on concrete properties. The incorporation of fibres in concrete (such as steel, glass, synthetic and natural fibres) has been found to improve on concrete properties (Zhang *et al.*, 2018; Ahmad *et al.*, 2019). However, there have been limited studies on the application of natural fibres (Banana, sisal, hemp, coconut, jute fibres, among others) in concrete (Xiong *et al.*, 2018; Elbhiery *et al.*, 2020). Banana fibres have good strength performance properties, are environment-friendly, less expensive and readily available in form of waste where pseudo-stems are left to rot in plantations (Elbhiery *et al.*, 2020). The fibres in these pseudo stems could be extracted and utilized to improve concrete properties (Ellen *et al.*, 2018). There was therefore a need to investigate on Banana fibres as reinforcement for concrete.

1.3 Research Objectives

1.3.1 Main Objective

The main objective of this study was to investigate the Effect of Banana fibres on the mechanical and microstructural properties of concrete.

1.3.2 Specific Objectives

The Specific objectives were:

1. To determine the physical and mechanical properties of Banana fibres;
2. To assess the effect of Banana fibre length and fibre content on the compressive, tensile and flexural strengths of concrete;

3. To characterize the microstructure of FRC and see changes in phases and compare with plain concrete and;
4. To model the behaviour of Banana fibres in concrete.

1.4 Research Questions

1. What is the density, average diameter and tensile strength of Banana fibres?
2. What is the effect of Banana fibres on the compressive, tensile and flexural strengths of concrete?
3. What is the effect of Banana fibres on concrete microstructure?
4. How can the behaviour of Banana fibres in concrete be modelled in Finite Element Methods?

1.5 Research Justification

Uganda is the 10th Banana growing country in Africa with the average annual production between 2018-2020 was 582,839 tons (AtlasBig.com, 2018). This implies that after cutting-off the bunches, more pseudo stems would be generated as an agricultural waste and left to rot in plantations. The fibres in these pseudo stems could be extracted and utilized to improve concrete properties. Natural fibres have; high tensile strength, low elongation at break, are readily available, environment-friendly and less costly (Zhang *et al.*, 2018).

1.6 Significance of the Research

The research will lead to a better understanding of the properties of Banana fibres; how fibre incorporation in concrete affects the mechanical and microstructural properties of concrete, and finally, how these properties relate when numerically modelled in ABAQUS FEM software. This will be a very attractive area and will play a pivotal role in; improving concrete properties, creating opportunities to the local communities involved in fibre extraction process; and finally extend the novel body of knowledge in using locally available materials to improve concrete properties.

1.7 Scope of the Research

1.7.1 Geographical Scope

The research was carried out at Kyambogo University in Uganda; Banana fibres were extracted from Kibaale District; Concrete ingredients were sourced from Karuma Hydropower Project site. Laboratory tests were conducted from Makerere University, Busitema University and Karuma Hydropower Project site.

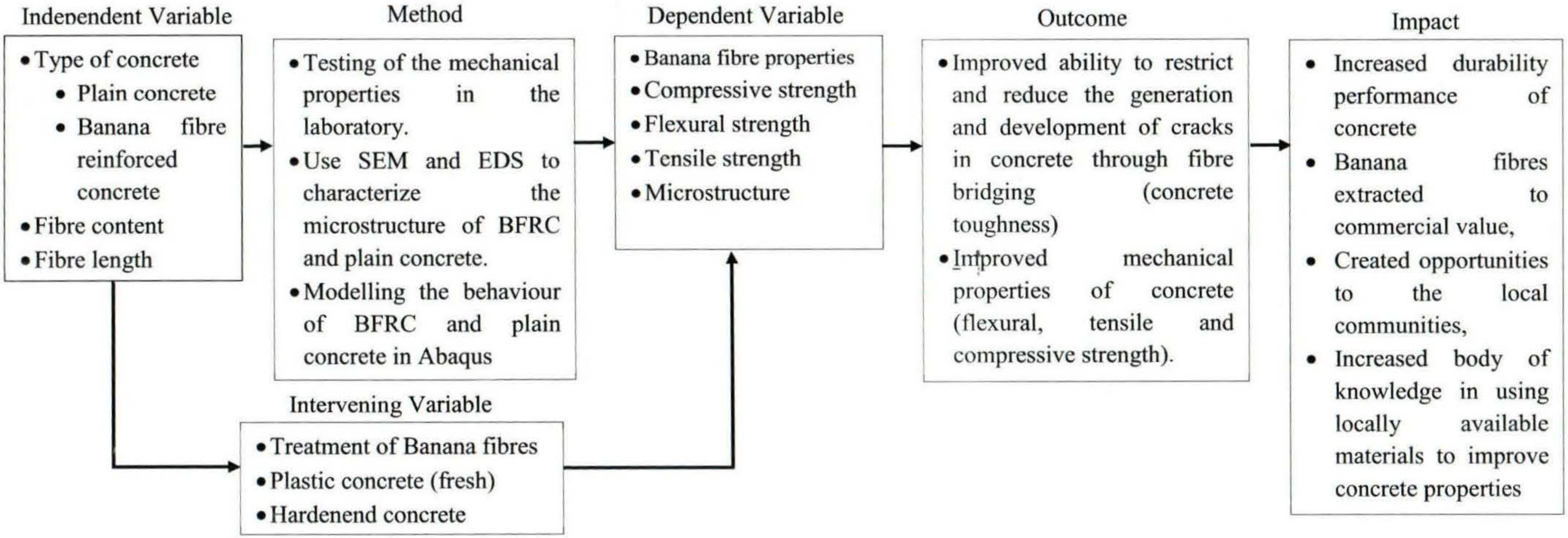
1.7.2 Content scope

- The Banana fibres were extracted, treated, and their properties determined in the laboratory. Fibres were later chopped to 40 mm, 50 mm and 60 mm length.
- A total of 288 samples were prepared from the C20/25 Concrete Mix design comprising six (06) mixes for plain concrete (reference concrete) and Banana fibre reinforced concrete of varying fibre content (0.00 %, 0.10 %, 0.25%, 1.00%, 1.50%, and 2.50 %).
- The samples were tested in the laboratory at 14 and 28 days for mechanical properties (compressive, spilt tensile and flexural strengths) using universal testing machine (UTM); and microstructural properties using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS/XRD)
- ABAQUS FEM software was used to model plain concrete and Banana fibre reinforced concrete and the results compared.

1.7.3 Time Scope

September 2019 to March 2021

1.8 Conceptual framework



Independent Variable

- Type of concrete
  - Plain concrete
  - Banana fibre reinforced concrete
- Fibre content
- Fibre length

Method

- Testing of the mechanical properties in the laboratory.
- Use SEM and EDS to characterize the microstructure of BFRC and plain concrete.
- Modelling the behaviour of BFRC and plain concrete in Abaqus

Dependent Variable

- Banana fibre properties
- Compressive strength
- Flexural strength
- Tensile strength
- Microstructure

Outcome

- Improved ability to restrict and reduce the generation and development of cracks in concrete through fibre bridging (concrete toughness)
- Improved mechanical properties of concrete (flexural, tensile and compressive strength).

Impact

- Increased durability performance of concrete
- Banana fibres extracted to commercial value,
- Created opportunities to the local communities,
- Increased body of knowledge in using locally available materials to improve concrete properties

Intervening Variable

- Treatment of Banana fibres
- Plastic concrete (fresh)
- Hardenend concrete

Figure 1.1: Research Conceptual Framework

1.9 Chapter Summary

The main objective of the research was to study the Effect of Banana Fibres on the Mechanical and Microstructural Properties of Concrete. Detailed over view of the study has been provided under the following components: - introduction, problem statement, research objectives and significances. The key variables have also been identified and schematically presented under the conceptual framework as well as the scope of the research being provided.

CHAPTER- 2 : LITERATURE REVIEW

2.1 Introduction

This Chapter presents a review of relevant studies carried out on Banana fibre reinforced cement-based composites in order to establish a state-of-engineering knowledge.

2.1.1 Fibre Reinforced Concrete

Fibre reinforced cement-based composites is one of the discovered resilient construction materials (Mobasher, 2012). The concept of Fibre Reinforced Concrete (FRC) is discussed by many scholars (Gram, 1983; Zollo, 1997; ACI 544.1R-96, 2002; Bentur & Mindess, 2007; CEB-FIP Model Code , 2010; Zongjin, 2011; Mobasher, 2012; ASTM C125, 2016; ACI 544.4R-18, 2018), among others. ASTM C125 (2016) seems to provide a simplified definition of fibres as slender filaments (discrete, bundles, networks or strands of natural or manufactured materials) that may be distributed uniformly in a fresh cementitious mixture. ACI 544.4R-18 (2018) defines Fibre-reinforced concrete (FRC) as concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibres.

2.1.2 Types of Fibres and their limitations

Many publications (ACI 544.1R-96, 2002; Bentur & Mindess, 2007; ASTM C1116/C1116M-10a, 2015; Chandrasekar *et al.*, 2017; Koohestani *et al.*, 2019; Ahmad *et al.*, 2019; Chandramouli *et al.*, 2019), among others; provide information on the different fibre types and their origin. Based on ASTM C1116/C1116M-10a (2015), there are four categories (types) of FRC based on material and these include, Type I- Steel, Type II- Glass, Type III- Synthetic and Type IV- Natural fibres and are briefly explained in the following section.

Type I: Contains stainless steel, alloy steel, or carbon steel fibres (ASTM C1116/C1116M-10a, 2015). Steel fibres are however more susceptible to severe corrosion, a major factor responsible for changes in the mechanical properties of the composite material (Bentur & Mindess, 2007).

Type II: Contains alkali-resistant (AR) glass fibres (ASTM C1116/C1116M-10a, 2015). Glass fibres have low resistance to moisture, sustained loads, and cyclic loads; carbon fibres have low impact resistance, low ultimate strain, and is relatively expensive (Zongjin, 2011).

Type III and Type IV- Synthetic and Natural fibres: Fibres for which documentary evidence can be produced confirming their resistance to deterioration when in contact with the moisture and alkalis present in cement paste and the substances present in admixtures throughout the anticipated useful life of the structure (ASTM C1116/C1116M-10a, 2015). Synthetic fibres have excellent strength performance characteristics but the only drawback is the effect on environment (Mallick, 2008).

2.1.3 Role of Fibres and performance mechanism in Concrete

The mechanism of fibre performance was presented by Li and Wu (1992) when they considered a composite sample subject to varying tensile loading and observed an increase in load carrying capability of the composite matrix prior to the formation of the cracks. A review by Zhang *et al.* (2018), identified three fundamental mode of action of fibres in concrete and these include, anti-cracking, reinforcing, and toughening; and are briefly explained ;

- The action of anticracking; relates to the fibres' ability to restrict and reduce the generation and development of cracks in concrete.
- The reinforcing action; relates to the improvement of the mechanical properties (flexural, tensile and compressive strength) of concrete.
- The toughness action; is related to fibre bridging that increases concrete toughness after cracking. According to Zollo (1997), bridging action prevent debonding, rupture and pull-out of fibres which prevents cracking and crack propagation due

to sharing and/or redistribution of loads and stresses between matrix and fibres (Mobasher, 2012). This provides post-cracking load carrying capacity under tension, bending, and shear due to the formation of hinges in the matrix during cracking where loads and stresses are redistributed (ACI 544.4R-18, 2018) resulting in an ascending stress–strain curve; generally referred to as strain hardening (Bentur & Mindess, 2007).

2.1.4 Factors governing FRC performance

A number of factors governing FRC performance have been published by a host of scholars (Zollo, 1997; Klemm *et al.*, 1998; ACI 544.1R-96, 2002; Chandramouli *et al.*, 2019; Girijappa *et al.*, 2019) among others as summarised . Also Figure 2.1 shows the performance of fibres in concrete.

- Fibre content (amount of fibres added to a concrete mix, expressed as a percentage of the weight of cement in the mix).
- Length of the fibres.
- Fibre-matrix adhesion (bond or anchorage of the fibre reinforcement).
- Fibre-alignment, distribution, and treatment.

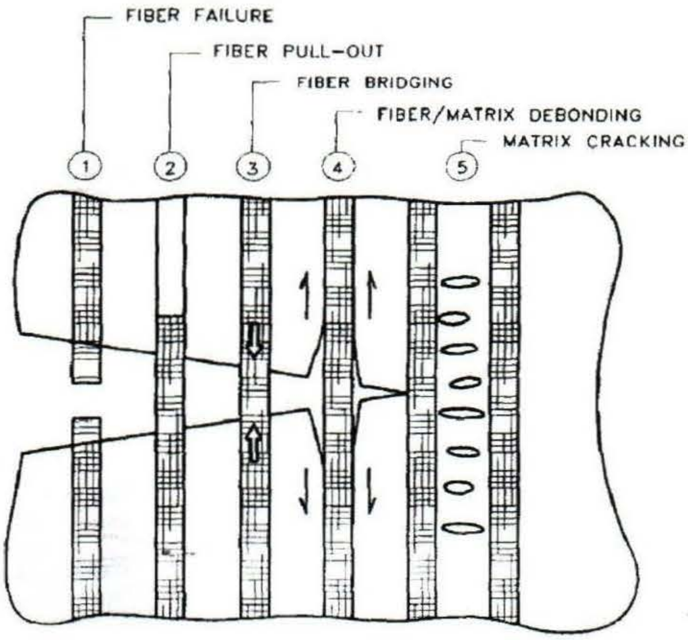


Figure 2.1: Energy-absorbing fibre/matrix mechanisms (Zollo, 1997)

2.2 The Need for Natural Fibres

2.2.1 Introduction

Natural Fibres have attracted much attention (Li *et al.*, 2006; Mallick, 2008; Mobasher, 2012; Chandrasekar *et al.*, 2017; Koohestani *et al.*, 2019; Zhang *et al.*, 2018; Ahmad *et al.*, 2019; Elbhiery *et al.*, 2020) among others, for use as reinforcing agent in composite materials; and nowadays are considered as potential substitute for Non-renewable synthetic fibres (Mukhopadhyay & Fangueiro, 2009). The utilization of natural fibres is mostly reported in reinforcing various composite materials but their application in concrete is still limited hence requiring detailed investigations (Elbhiery *et al.*, 2020).

2.2.2 Classification of Natural fibres

Published information (Bentur & Mindess, 2007; Ellen *et al.*, 2018; Koohestani *et al.*, 2019; Ahmad *et al.*, 2019; Chandramouli *et al.*, 2019) among others, is available on natural fibre classification. A review by Ahmad *et al.* (2019), seems to provide a detailed classification of plant fibres as follows: (i) Bast fibres, (ii) Leaf fibres, (iii)

Stalk (iv) Fruit (v) Grass (vi) Seed fibres, (vii) Wood. These are summarised in Figure 2.2 . It is observed that Banana fibres are classified as leaf fibres.

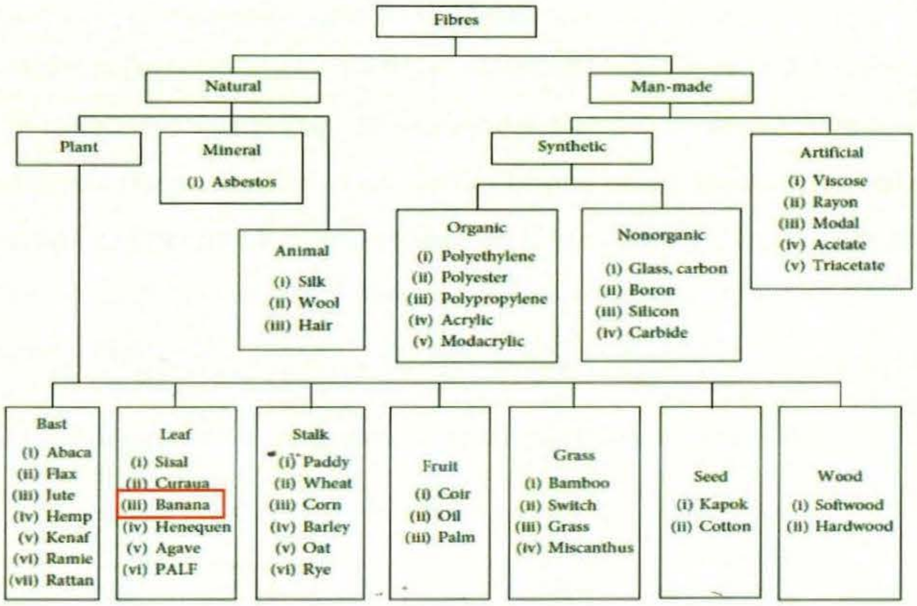


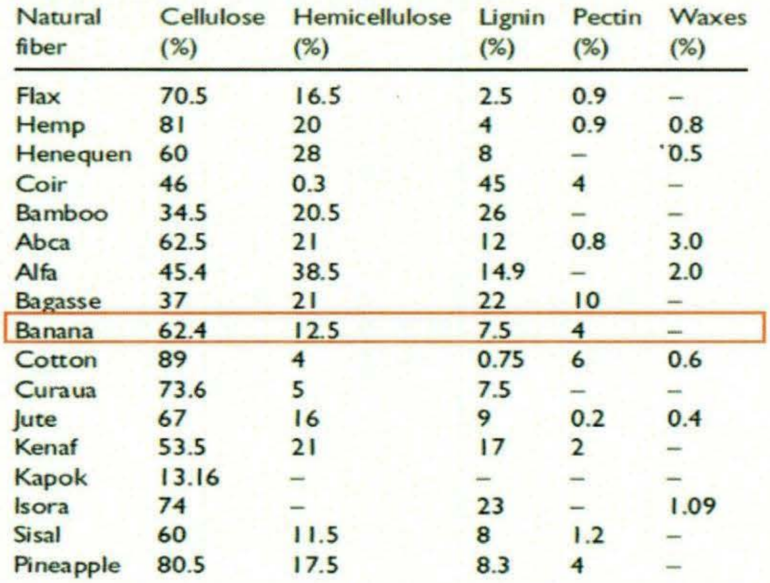
Figure 2.2: Fibre Classification; Source: (Ahmad et al., 2019)

2.2.3 Chemical properties of Natural Fibres and Performance Limitations

The main components of natural fibres include; cellulose, hemicellulose, lignin, pectins, and waxes (Ahmad *et al.*, 2019). Table 2.1 lists the different classification of natural fibres and their respective properties. There exists variation in the tested parameters from different publications.

Studies conducted on the performance of natural fibres (Mohanty *et al.*, 2005; Mallick, 2008) revealed durability shortcomings related to the inability to resist both external and internal damage; where external damage relate to effects arising out of: moisture absorption, biological micro-organisms, sulphate or chloride attack; while Internal damage is majorly due to compatibility problems between fibres and alkaline-cement paste environment. The presence of organic substances (waxes, lignin, and pectin); render fibres susceptible to degradation by the high alkaline environment within the cement; poor interfacial adhesion, poor resistance to moisture absorption and biological attack (Klemm *et al.*, 1998; Mohanty *et al.*, 2005). Gram (1983) reported on the deleterious effect of high alkaline environment in the Portland cement on sisal and coir fibres; the alkaline environment dissolved the organic substances and weakened the fibre structure (Wallenberger & Norman, 2004). A review by Mukhopadhyay & Fangueiro (2009), revealed high moisture absorption of most natural fibres constituents caused by the presence of hydroxyl and other polar groups as part of their constituent. The factors render the use of natural fibre reinforced composites less attractive (Abd *et al.*, 2007). Inspite of the shortcomings of natural Fibre Reinforced Concrete, the merits of natural fibres outweigh the demerits and most of the shortcomings have remedial measures that can be taken in form of fibre surface modification (treatments) (Mindess, 2011; Girijappa *et al.*, 2019).

Table 2.1: Fibre composition of Plant fibres, (Ahmad et al., 2019)

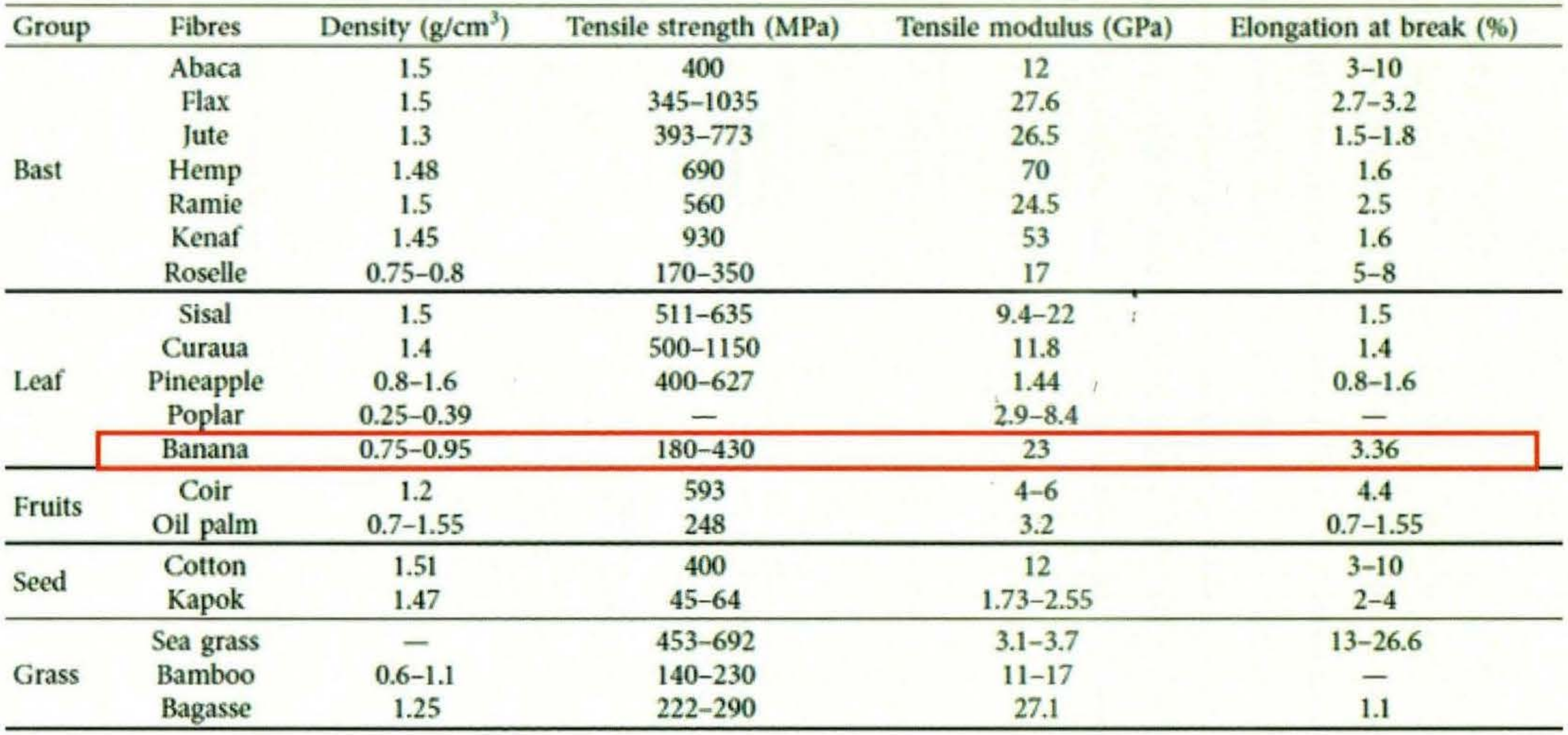


Natural fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)
Flax	70.5	16.5	2.5	0.9	–
Hemp	81	20	4	0.9	0.8
Henequen	60	28	8	–	0.5
Coir	46	0.3	45	4	–
Bamboo	34.5	20.5	26	–	–
Abca	62.5	21	12	0.8	3.0
Alfa	45.4	38.5	14.9	–	2.0
Bagasse	37	21	22	10	–
Banana	62.4	12.5	7.5	4	–
Cotton	89	4	0.75	6	0.6
Curaua	73.6	5	7.5	–	–
Jute	67	16	9	0.2	0.4
Kenaf	53.5	21	17	2	–
Kapok	13.16	–	–	–	–
Isora	74	–	23	–	1.09
Sisal	60	11.5	8	1.2	–
Pineapple	80.5	17.5	8.3	4	–

2.2.4 Mechanical properties of Plant Fibres.

Table 2.2, shows a summary of the mechanical properties of Plant fibres in the literature as presenteb by (Ahmad *et al.*, 2019)

Table 2.2: Mechanical Properties of different natural fibres, (Ahmad et al., 2019)

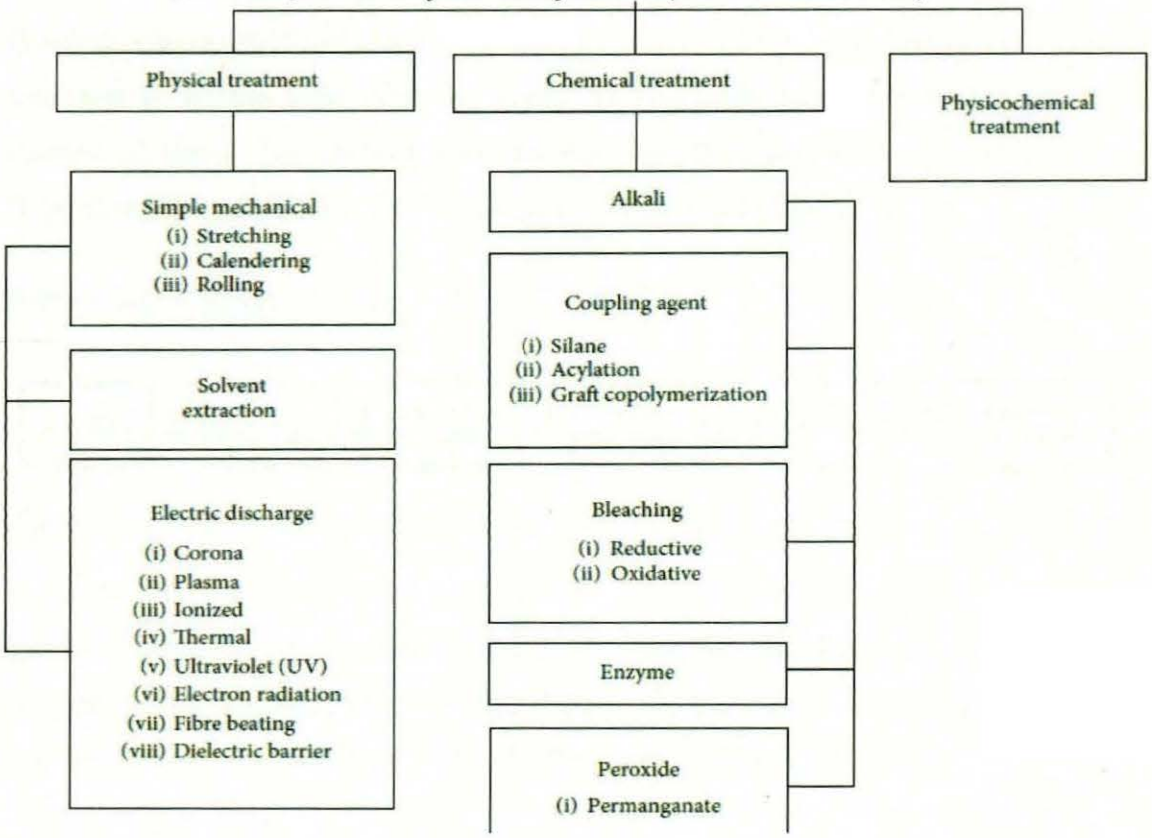


Group	Fibres	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Bast	Abaca	1.5	400	12	3–10
	Flax	1.5	345–1035	27.6	2.7–3.2
	Jute	1.3	393–773	26.5	1.5–1.8
	Hemp	1.48	690	70	1.6
	Ramie	1.5	560	24.5	2.5
	Kenaf	1.45	930	53	1.6
	Roselle	0.75–0.8	170–350	17	5–8
Leaf	Sisal	1.5	511–635	9.4–22	1.5
	Curaua	1.4	500–1150	11.8	1.4
	Pineapple	0.8–1.6	400–627	1.44	0.8–1.6
	Poplar	0.25–0.39	—	2.9–8.4	—
	Banana	0.75–0.95	180–430	23	3.36
Fruits	Coir	1.2	593	4–6	4.4
	Oil palm	0.7–1.55	248	3.2	0.7–1.55
Seed	Cotton	1.51	400	12	3–10
	Kapok	1.47	45–64	1.73–2.55	2–4
Grass	Sea grass	—	453–692	3.1–3.7	13–26.6
	Bamboo	0.6–1.1	140–230	11–17	—
	Bagasse	1.25	222–290	27.1	1.1

2.3 Pre-treatment of Natural Fibres

There are a series of research studies (Mohanty *et al.*, 2005; Abd *et al.*, 2007; Mukhopadhyay & Fangueiro, 2009; Susheel *et al.*, 2009; Karsli & Aytac, 2014; Chandrasekar *et al.*, 2017; Koohestani *et al.*, 2019; Ahmad *et al.*, 2019) among others on pre-treatment methods of natural fibres. A review by Ahmad *et al.* (2019), identified three pre-treatment methods of natural fibres; Physical/plasma treatments (improve strength, modulus, and elongation properties), Chemical treatment (improve on the interfacial properties of the fibre-matrix and the durability of the fibre in cement-based composites), while Physico-chemical treatments provide clean and fine fibrils with very high cellulose content. These are presented in the following Table 2.3 .

Table 2.3; Fibre Surface Modification (Ahmad et al., 2019)



According to a review conducted by Susheel (2009), Physical/plasma treatment was reported as the most effective method; but its application is limited by scarcity of tools, complexity of the plasma state and limited experimental studies (Mukhopadhyay &

Fangueiro, 2009). This was justified by a review conducted by (Koohestani *et al.*, 2019). Accordingly, plasma treatment was not adopted.

2.3.1 Effect of Chemical treatment methods on fibre properties.

The effects of the different chemical treatment methods were reviewed. According to Sreekala *et al,* (2000) cited by Mohanty *et al,* (2005), Chemical pretreatment affect the mechanical properties of natural fibres. The reduction was attributed to fibre disintegration through delignification of the non-cellulosic materials (Polona, 2010). According to Koohestani *et al,* (2019), Maleated, acetylation, alkalization, and silane treatments displayed a respective improvement in tensile strength of natural fibres by (32~58) %, (27~56) %, (4~54.5) %, and (20~45) %. There were marginal (20 %) impact of alkalization treatment on the properties of fibres compared to other methods (Sahu & Gupta, 2019). A review by Ahmad *et al,* (2019), identified Alkalization treatment to be the most effective, cheap and normally used chemical treatment method of fibres. The reaction between Alkalisation is presented in a review by (Chandrasekar *et al,* 2017). This is schematically shown in figure 2.3.

$\mathrm{Fibre - OH + NaOH \rightarrow Fibre - O - Na^{+} + H_2O}$ ....Equation 2.0

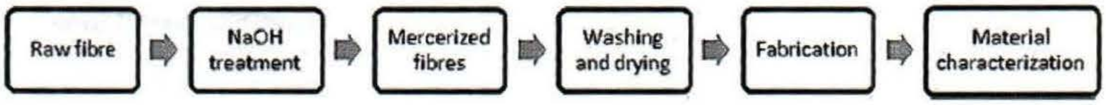


Figure 2.3: Fibre Treatment Process (Chandrasekar et al., 2017)

From the equation, it is observed that fibres are immersed in sodium hydroxide (NaOH) solution which then reacts and removes the hemicellulose, lignin (delignification) and wax. This exposes cellulose and increases surface roughness, and improves interfacial bonding strength (Pickering *et al.*, 2016).

A number of research studies and reviews (Susheel *et al*, 2009; Kushwaha & Kumar, 2009; Yan *et al*, 2012; Venkateshwaran *et al*, 2013; Karsli & Aytac, 2014; Manalo *et al*, 2015; Chandrasekar *et al*, 2017; Koohestani *et al*, 2019; Ahmad *et al*, 2019) among others, were conducted to determine the effect of sodium hydroxide (NaOH) solution on the mechanical properties of both plant fibres and plant fibre reinforced composites.

It is reported (Koohestani *et al*, 2019) that alkaline treatment increased the surface tension of sisal fibres which resulted in improved compressive strength and reduced absorption of the composite.

Experimental investigation on coir fibre-based epoxy composite treated with different alkali concentrations (2, 4, 6 and 8 %) and untreated for 10 days by Karthikeyan cited in Chandrasekar *et al*., (2017) revealed improvement in impact strength for alkali-treated fibre composites compared to untreated fibre-based composites.

A review carried out by Chandrasekar *et al,* (2017), regarding the characterisation of alkali treated natural fibres and their composites, identified an optimum concentration of NaOH treatment and treatment time, for the increased efficiency of fibre performance.

Venkateshwaran *et al* (2013) carried out a study on the effect of fibre surface treatment on the mechanical and visco-elastic behaviour of Banana/epoxy composite. They used alkali (NaOH) of various concentrations (0.5 %, 1 %, 2 %, 5 %, 10 %, 15 % and 20 %) by weight for 30 minutes. They observed that 1 % NaOH treatment produced the best tensile, flexural and impact properties.

Yan *et al* (2012) compared the mechanical strengths of alkali-treated and non-treated flax, linen and bamboo fabric-reinforced epoxy composites. They concluded that 5 % alkali-treated fibre-reinforced composites exhibited higher mechanical strength than untreated composites, irrespective of the fibre types.

Kushwaha & Kumar (2009) carried out a study on the effect of NaOH on bamboo fibre mat-reinforced epoxy composites. The findings identified that the mechanical properties of the composite were enhanced by fibre treatment of 5 % NaOH. Accordingly, 5 % Sodium Hydroxide was adopted and used in the research.

2.4 Effect of fibres on the Mechanical performance of FRC

Many research studies, (Savastano *et al*, 2000; Li *et al*, 2006; Barros *et al*, 2016; Mukhopadhyay & Bhattacharjee, 2016; Prasannan *et al*, 2018; Chandramouli *et al*, 2019; Elbhiery *et al*, 2020; Dhawan *et al*, 2020), among others; have reported on the effect of natural fibres on the mechanical performance of concrete.

Elbhiery *et al* (2020) analysed the performance of Banana fibre bars (treated with NaOH) on the mechanical properties of reinforced concrete beams, Results indicated that the compressive strength of concrete was not affected; there was however, 2 % improvement in the flexural strength of the concrete.

(Dhawan *et al* (2020) investigated the mechanical properties of concrete containing fly ash, bagasse ash and Banana fibre. Banana fibres of 40 mm length and 0 %, 2.5 % and 5 % fibre content by weight of cement. Observations revealed that when compared with conventional concrete; Banana fibres resulted in; 6 % and 10 % improvement in compressive and flexural strengths respectively corresponding with 2.5 % fibre content. However, reduction in strength was observed when the fibre content was increased. Investigation on the mechanical properties of cement-lime mortar reinforced with plantain fibres by Humphrey, (2020) where experimental samples were cast with 65 mm fibre length and 0, 0.25, 0.5, 0.75, and 1 % fibre content; observed, 13.80 % and 23.4 % increase in tensile and compressive strengths respectively. The effect of Banana fibre content on the ductility properties of concrete (compressive and split tensile strengths) were investigated (Chandramouli *et al.*, 2019). Samples were prepared by mixing 40 mm fibre length in different fibre contents ranging from 1 % to 6 %. Observations showed an improvement in compressive and split tensile strengths of concrete. A study on the performance of Banana fibre reinforced concrete under uniaxial and biaxial tensile stress by Ellen *et al.* (2018) while focusing on 0.50 % and 1.0 %, fibre concentration and 30 mm fibre length treated with 5 % NaOH; discovered an improvement in the flexural strength of concrete. Prasannan *et al* (2018) investigated on the strength properties of concrete (compressive strength, split tensile strength and flexural strength) reinforced with sisal and Banana fibres respectively. Parameters used were, fibre content (0.5 %, 1 %, 1.5 %) and fibre length, 30mm length. Experimental outcome showed a respective increase in compressive, flexural and tensile strengths of 0.5 %, 2.5 % and 5.2 % at 1.5 % fibre content. Investigations into the utilisation of treated Banana fibres at (0.3 % and 0.6 % fibre content and 20 mm fibre length) in concrete by Mukhopadhyay & Bhattacharjee (2016), observed an improvement in compressive strength corresponding to 0.3 % fibre content. They further discovered that increasing fibre content, resulted in reduction in strength and this limitation was attributed to balling effect of fibres.

2.5 Effect of fibres on the Concrete Microstructure

Concrete has a highly heterogeneous and composite structure (micro and macro); that is constituted by, the type, amount, size, shape, and distribution of the available phases. The macro elements are visible to the human eye while micro elements are resolved by the help of a microscope; hence the term microstructure refers to the phases, morphology (grain, particle sizes and distribution) and chemical composition of the material which can readily be seen with the help of a microscope. Aggregates, bulk cementitious matrix and the interfacial transition zone (ITZ-cement-aggregate) and Fibre-Matrix Interfacial zone constitute the microstructure of concrete (Mehta & Monteiro, 2006). The study of microstructure can reveal the relationship between a particular microstructural feature and a specific physical, chemical or engineering properties of the material (Brandon & Kaplan, 2008). These properties affect the behaviour of cementitious materials and therefore must be characterized (Bentur & Mindess, 2007).

The Scanning Electron Microscope, (SEM) is one of the most multipurpose instruments used to investigate and analyse microstructural characteristics of solid objects including cement and concrete (Nemati & Stroeven, 2001). According to Goldstein *et al.* (2018), the Scanning Electron Microscope is an instrument that creates magnified images which reveal microscopic-scale information on the size, shape, composition, crystallography, and other physical and chemical properties of a specimen. Studies on the effect of fibres on the microstructure of materials, involving the use of the SEM have been made available (Nemati & Stroeven, 2001; Savastano Jr *et al.*, 2005; Sivaraja *et al.*, 2010).

Savastano Jr *et al* (2005) studied the microstructure of Sisal and Eucalyptus composites, in terms of morphological and bonding characteristics under SEM

(Secondary Electron (SE) and Back-Scattered Electron (BSE) imaging) and Energy Dispersive X-ray Spectroscopy (EDS/XRD). BSE images and EDS analyses revealed improvement in the fibre-matrix transition zone.

Sivaraja *et al* (2010) carried out an experimental investigation on the durability of coconut coir and sugarcane bagasse natural fibres. The research focused on mechanical and microstructural properties of fibres and fibre reinforced concrete. Among other observations, microstructure (SEM and EDS) analysis confirmed excellent adhesion between the boundary of fibre-matrix transition zone.

Tehmina *et al* (2014) used Field Emission Scanning Electron Microscope (FESEM) to study the microstructure properties (Interfacial Transition Zone (ITZ) between the aggregates and the paste) of high performance fibre reinforced concrete containing up to 3 % Chopped Basalt Fibres. Results revealed an improvement in ITZ.

Humphrey (2020) examined the microstructural properties of cement mortar and plantain pseudo stem samples using scanning electron microscopy (SEM). Results revealed that cement mortar samples had no observed cracks. Microcracks were observed with plantain pseudo stem which were attributed to manufacturing or handling deficiencies.

2.6 Modelling the Behaviour of BFRC and Plain concrete

Concrete is a heterogeneous composite that exist as a continuum, (a body that can be sub-divided into infinitesimal elements) where the mechanical behaviour of materials can be modelled as a continuous mass rather than a discrete element. On the other hand, micromechanics by homogenization, allows detailed modelling of the internal structural arrangement of a composite material by treating each constituent as a continuum (Mishnaevsky Jr, 2007). Analytical approaches (such as mean field approaches) and computational methods are available to model the behaviour of composites. Mean field approaches are devoid of a requirement for domain discretization. Computational homogenization approaches [finite elements, fast Fourier transform methods, finite volumes, finite differences and boundary elements.]

is a more direct approach (Bargmann *et al*., 2018). The concept of Representative volume element (RVE) has been a widely used homogenization-based multi-scale constitutive method in finite element analysis to study the effect of micromechanical properties (strength, deformation and failure) on the mechanical properties of composites (Xiong *et al*., 2018). A number of definitions for RVE have been discussed (Hill, 1963; Gitman *et al*, 2006). Hill (1963) defined the RVE as a sample of a heterogeneous material that is entirely typical of the whole mixture on average, and contains a sufficient number of inclusions for the apparent properties to be independent of the surface values of traction and displacement, so long as these values are macroscopically uniform.

The concept of representative volume element (RVE) was introduced to relate the macroscopic properties of materials with the microscopic properties of the constituents and material structure respectively (Gitman *et al*., 2006). According to Sciegaj *et al* (2020), RVEs have been applied in modeling representative samples of the material at a haphazard scale of detail where the macroscopic loading information is defined on each RVE while applying suitable boundary conditions. They take into considerations of the volume fractions of the inclusions and the individual contribution from each composite (Barbero, 2008). The definitions in general reveal that the RVE should contain sufficient information on the microstructure but should be adequately smaller than the macroscopic structural dimensions (Gitman *et al*., 2006).

Breuer & Stommel (2019) carried out a numerical modelling of short fibre reinforced thermoplastics with discrete fibre orientation and fibre length distribution using RVE homogenization technique. The research focused on the influence of fibre packing, fibre shape, bonding of the fibres to the matrix, fibre length distribution and fibre orientation.

Wang *et al* (2016) carried out Micromechanical finite element Modeling of Fibre reinforced composites with statistically equivalent random fibre distribution and developed a new algorithm for generating random representative volume elements

(RVEs). It was found that the proposed method presented a good match with experimental results.

Gitman *et al* (2006) analysed the concept of the representative volume element (RVE) with a focus on its existence in different stages of loading, elastic-hardening-softening and also proposed a method to determine the size of RVE for random three-phase (matrix, inclusion and ITZ) quasi-brittle materials.

In the work by (Barbero, 2008) a number of examples were provided for the determination of the RVEs of different composite materials including concrete.

Sciegaj *et al.* (2020) in their study on Upscaling of three-dimensional reinforced concrete representative volume elements (RVE) to effective beam and plate models. The response of three-dimensional reinforced concrete RVEs was homogenised to macroscopic beam and plate models; special modified finite elements were constructed. They observed among others that the effective response of the RVE followed the expected response of a reinforced concrete cross-section in tension and bending.

2.7 Chapter Summary

Research carried out on the effect of Banana fibres on concrete properties, has either concentrated on a single fibre length and investigated the fibre content. These include Ellen *et al* (2018), Prasannan *et al* (2018), Chandramouli *et al* (2019); Dhawan *et al* (2020), and Humphrey (2020). All showed that Banana fibres improved the flexural and compressive properties of concrete. The effect of natural fibres on microstructure was investigated by Savastano Jr *et al* (2000), Nemati & Stroeven (2001), Sivaraja *et al* (2010), Tehmina *et al* (2014). These have mainly concentrated on Sisal, eucalyptus, coconut, sugarcane, basalt fibres but not banana fibres. The available study on the effect of banana fibres on microstructure by Humphrey (2020), focused on the application of the fibres in mortar but not concrete. Finally, studies on the application of Homogenization Techniques of Representative Volume Element (RVE) in finite element analysis, focused on sisal, coconut, hemp, glass and Plain concrete but not Banana fibres.

Based on the available literature review, there are limited number of studies that address the influence of different Banana fibre lengths and fibre contents on concrete properties to establish the: (a) Optimum fibre length and the corresponding fibre content; (b) Effect of Banana fibres on the microstructure of concrete; and (c) Behaviour of Banana fibres in concrete. This was therefore the basis of the research.

CHAPTER- 3 : RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents a detailed description and explanation of the various steps that were undertaken in this study. The independent variables of the experimental study were: (1) Plain concrete; (2) Banana fibre reinforced concrete; (3) Fibre content; and (4) Fibre length. The influence of these variables on the mechanical (compressive, flexural and tensile strength) and microstructural properties of concrete was experimentally assessed. Finally, a 3D Representative Volume Element (RVE), micromechanical model of Banana fibre reinforced concrete was modeled in ABAQUS software to assess the influence of fibres in concrete.

3.2 Experimental Set up (Research Design)

3.2.1 Research approach

A systematic experimental program was designed to investigate the effect of Banana fibres on the mechanical and microstructural properties of concrete. A total of 288 samples of C20/25 concrete mix were prepared for plain concrete (reference concrete) and Banana fibre reinforced concrete and tested to determine mechanical and microstructural properties of concrete. Table 3.1 presents the parameters that were tested with their corresponding sample sizes, concrete type and quantities. The variables were, fibre length and percentage fibre content as shown in Table 3.2.

Table 3.1: Parameters Tested at 14 and 28 days

Parameter	Plain concrete	Fibre reinforced	Dimension (mm)
Compressive strength	6 cubes	90 cubes	150x150x150
Flexural strength	6 beams	90 beams	150x150x350
Split tensile strength	6 cylinders	90 cylinders	200Øx300

Table 3.2: Variables for the experiment (fibre length and fibre content)

Fibre length (mm)	40	50	60
Fibre content	0.10%	0.10%	0.10%
	0.25%	0.25%	0.25%
	1.00%	1.00%	1.00%
	1.50%	1.50%	1.50%
	2.50%	2.50%	2.50%

As shown in Table 3.2, the fibre length was varied from 40 mm, 50 mm and 60 mm. for each fibre length, the fibre content was varied from 0.10 %, 0.25 %, 1.00 %, 1.50 % and 2.50 %. For each concrete type, fibre content and fibre length, six (06) each of cubes, beams and cylinders were cast; out of which three (03) were tested at 14 days and 28 days respectively as shown in Table 3.3 and 3.4 .

Table 3.3: Samples cast for every Test parameter

Concrete age	14 days	28 days
Fibre length	0.0	0.0
0.0%	3	3

Table 3.4: Samples of Banana fibre reinforced concrete cast for each parameter

Concrete age	14 days			28 days		
Fibre length	40	50	60	40	50	60
0.10%	3	3	3	3	3	3
0.25%	3	3	3	3	3	3
1.00%	3	3	3	3	3	3
1.50%	3	3	3	3	3	3
2.50%	3	3	3	3	3	3

3.2.2 Sample coding

To ease identification throughout the research process, samples were assigned a unique identity code typical of the type of concrete, fibre length, fibre content, and concrete age; for example, F5121D (F- Banana Fibres; 5 -Fibre length (cm); 1-Fibre content in ascending order; 2- age of concrete at 2 weeks (14 days) and 1D- Casting date (1st December, 2020)

3.3 Data Collection

3.3.1 Materials

Banana fibres, cement, coarse and fine aggregates and water

3.3.2 Banana Fibres

a) Identification of the source of the Banana fibres

Banana fibres were obtained from Kyakyarwa village, Kibaale district; 250 km from Kampala, the capital city of Uganda. The Banana fibres were manually extracted from the Banana sheaths of the harvested pseudo stems. Figure 3.1 shows the Plantation of Banana Cultivar- Yangambi km5 in Kibaale District

Figure 3.1: Plantation of Banana where fibres were extracted in Kibaale District

b) Manual Extraction of Banana fibres by Scraping

The procedure followed during extraction of the Banana fibres was based on some of the exraction techniques for natural fibres presented in Mohanty *et al.*, (2005). The following steps were followed.

Tools and equipment

Metallic drum (for boiling the fibres), blunt wedge-like piece of wood (to scrap the fibres), and a wooden rod of 400 mm length and 40 mm diameter (to anchor the fibres during scrapping).

i. The cut Pseudo-stems were sliced into 600 mm maximum length (to ease handling); and boiled for a minimum of 6 hours to soften the sheaths and ease manual scrapping/extraction of the fibres.

ii. **Fibre extraction/scrapping platform:** Three (03) platforms (for faster fibre generation) of cut Banana pseudo-stem not exceeding 1200 mm length were arranged for manual fibre scrapping. They were firmly secured by 40 mm diameter piece of wooden rod, 200 mm into the ground, protruding 200 mm from the pseudo-stem where the sheaths were tied during scrapping;

iii. **Fibre Extraction/Scrapping:** Boiled sheaths were individually tied, squeezed and scrapped continuously using a blunt piece of wood to remove the Mesophyll/cortex layer which exposed the fibres.

iv. Extracted fibres were washed and then spread on a Tarpaulin to dry.

v. Fibres were then chopped into different fibre length (40, 50 and 60 mm); weighed and then parked. Figure 3.2, shows the extracted Banana fibres while Figure 3.3 shows Chopped Banana Fibres

Figure 3.2: Extracted Banana fibres

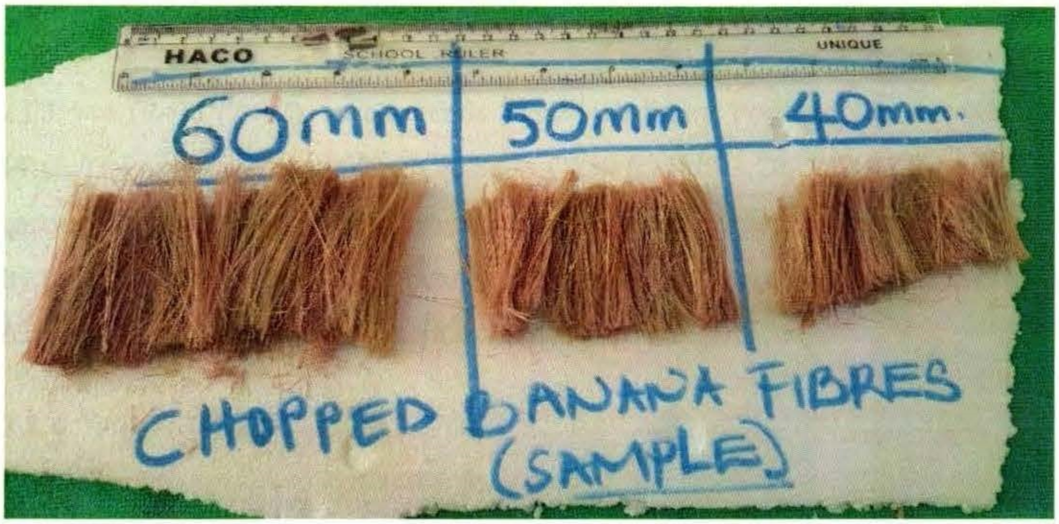


Figure 3.3: Chopped Banana Fibres

c) Treatment process of Banana fibres

Section 2.2.3 literature provides the durability performance limitations associated with natural fibres and mitigation measures which include treatment. Therefore, in this section, treatment was done using Caustic Soda, obtained from Sky Chem (U) LTD. The 1000 g of the Caustic Soda was carefully dissolved in 20 liters of distilled water to form a solution of 5 % Sodium hydroxide. Preparation of the solution was based on the different research studies presented in section 2.3.

Banana fibres were immersed in the solution for 60 minutes at room temperature and then thoroughly washed with tap water for a minimum of 10 minutes to remove the non-reacted alkali until the colour of the water coming out of the fibres was clear as shown in Figures 3.4, 3.5 and 3.6.

Figure 3.4: Caustic Soda (NaOH)

Figure 3.5: Treatment of Fibres

Figure 3.6: Washing of treated fibres using tap water

3.3.3 Cement

ACI 544.1R-96 (2002), recommends Type I Ordinary Portland Cement (OPC) for FRC. The cement complies with (ASTM C150/C150M - 20, 2020). Type III (high-early strength) cement can also be used in order to reduce hardening retardation caused by the glucose present in most natural fibre. For this research, CEM I 42.5 N - OPC, manufactured by Kampala Cement limited was used.

3.3.4 Aggregates

Crushed aggregates were obtained from the Karuma dam project. The geological classification of the rock was predetermined at the project site and categorised as granite-gneiss. For this research aggregates of maximum size 19 mm were used.

3.3.5 Water

Ordinary portable water was used

3.4 Material Tests

3.4.1 Tests on Banana Fibres

Fibre properties were determined in accordance with ASTM standards (ASTM C1116/C1116M-10a, 2015; ASTM D7357, 2019). Parameters that were investigated include, tensile strength, fibre density, average diameter, moisture content and elongation at break (%).

Single fibre tensile test was conducted using a Universal Instron Tester. The breaking load and breaking extension were recorded at the point of rupture. The Tensile strength of a single fibre was calculated using the following equation 3.1.

$$Tensile\ strength\ for\ a\ single\ fibre = \left[\frac{average\ force}{\pi \frac{d^2}{4}} = \frac{148.26 \times 0.00981}{\frac{22}{7} \times \frac{0.103^2}{4}} \right] \text{......Equation. (3.1)}$$

The average diameter of fibres was determined using the Scanning Electron Microscopy (SEM).

3.4.2 Tests on Cement

Chemical and physical test certificates were provided by Kampala cement limited (manufacture) on delivery of cement to the Karuma project site and are summarised in Table 3.5 and Table 3.6.

Chemical composition of cement

Table 3.5: Chemical composition of CEM I 42.5N, Kampala Cement-OPC, (Kampala Cement limited, 2019)

Chemical	SiO_2	CaO	Fe_2O_3	MgO	Al_2O_3	SO_3	LOI	I.R
Specification	N/A		6.0-max			3.0-max		<5
Result	22.86	65.08	4.07	1.95	5.05	2.41	1.12	1.33

Table 3.6: Physical Tests- Results of Kampala Cement- CEM I- 42.5N (Sinohydro, 2019)

Test Item		ASTM C150/C150M, (20, 2020)	Test Results
Blaine fineness (0.08 mm) % (m^2/g)		N/A	2.2
Specific surface Area, m^2/g			349.9
Consistency			27.8
Soundness, mm		≤ 10	0.5
Initial Setting Time, min		≥ 60.0	154
Final Setting Time, min		N/A	293
Compressive strength, MPa	2 days	$N \geq 10.0$	20.9
	28 days	≥ 42.5 and ≤ 62.5	48.1

3.4.3 Tests on Coarse and Fine Aggregates

The physical properties that were useful for mix computations were; aggregate type, sieve analysis, specific gravity, absorption, moisture content and unit weight.

Table 3.7: Grading Results of Fine Aggregates (Sinohydro, 2019)

		Percentage Passing, (%)						
Sizes (mm)	Sieve size	4.75	2.36	1.18	600	300	150	75
		No.4	No.8	No.16	No.30	No.50	No.100	No.200
0 ~ 4.75	Results	100.0	90.8	62.1	37.4	19.0	8.3	8.0
	ASTM C33/C33M-18, (2018)	95~100	80~100	50~85	25~60	5~30	0~10	0~3.0

Table 3.8: Grading Results of Coarse Aggregate (Sinohydro, 2019)

Aggregate Sizes	Percentage Passing (%)					
	Sieve size	19	12.5	9.5	4.75	2.36
4.75-19	Test Results	100	76.2	44.4	2.4	0.45
	ASTM C33/C33M-18, (2018)	90- 100	/	20-55	0-10	0-5

Table 3.9: Physical properties- coarse and fine aggregates (Sinohydro, 2019)

Test Item	**Specification**	**Test Results**	
	ASTM C33/C33M-18, (2018)	0-4.75	4.75-19
Fineness modulus, FM	2.3~3.1	2.86	
Water Absorption %	≤3	0.61	0.37
Saturated surface dry apparent density, (g/cm3)	(sand) ≥ 2.5 (Agg.) ≥ 2.55	2.80	2.85
Mica content (%)	≤ 2	0.00	
Fines < 0.075 mm (%)	≤ 3	2.74	
Flakiness Index, %	< 25		9.50
Elongation Index, %			11.60

3.5 Mix Design Preparation

3.5.1 Introduction

The mix design was prepared based on the philosophy that concrete should provide both adequate durability and strength of the structure. The selection of the desired strength was based on; the anticipated exposure conditions, the type of structure and aggregate characteristics as explained in the following sections.

3.5.2 Plain concrete

The Nominal mix design selected for both Plain and Banana fibre reinforced concrete was C20/25. The standard used for plain concrete was (ACI 211.1-91, 2002). Table 3.10 presents the calculated mix designs quantities. The step-by-step procedure followed during mix design preparation is given in Appendix-A. Table 3.10 presents the mix composition used in the experimental program;

Table 3.10: Research Mix Design-Plain Concrete

Grade	*Aggregates (mm)*	*Design Slump (mm)*	*W/C*	*Materials Quantity (kg/m^3)*			
				Water	Cement	coarse aggregates	Fine aggregates
C20/25	19	20-50	0.45	192	444	1166	709

3.5.3 Mix Design for the Banana Fibre Reinforced Concrete

The mix design for Banana fibre reinforced concrete was prepared in accordance with the provisions given in ACI 544.1R-96, (2002). The quantities of Banana fibres required in concrete were calculated based on the weight of cement. The calculated quantities are given in Table 3.11

Quantity of fibres required for every individual batch.

Volume of concrete required for each individual batch calculated using equation 3.2:

$\left[V_f \times C \times V_{FRC}\right] \times 1000\ (g) = \left[\frac{0.10}{100} \times 444 \times 0.1272\right] \times 1000 = 56.46g$... Equation. 3.2

V_f: $Fibre\ content, \%;\ C: total\ weight\ of\ cement, kg/m^3$

V_{FRC}: $Volume\ of\ FRC\ corresponding\ to\ batches\ of\ individual\ length\ of\ fibers.$

Table 3.11: Calculated Quantities of Banana Fibres used in the experiment

Fibre content	**Weight of fibres (kg/m^3)**
0.10 %	0.444
0.25 %	1.11
1.00 %	4.44
1.50 %	6.66
2.50 %	11.1

3.6 Concrete mixing, Compaction, Finishing and Curing

Mixing protocol

An electrically operated mechanical mixer with rotating pedals was used. The mixing protocol for plain concrete complied with ACI 211.1-91 (2002) while for Banana fibre reinforced concrete; ACI 544.1R-96 (2002), provides two methods of mixing: (1) Wet mixing (applies to hand mixing), and (2) Dry-compacted mixing. The wet mixing protocol was adopted for the study.

Precautions considered during Mixing operation

During mixing of Banana fibre reinforced concrete the following precautions were considered.

- Mixing protocol: the mixing protocol was Aggregates-Sand-Cement-Fibres-Water. This was to avoid balling effect (formation of balls or lumps of fibres during mixing)
- Fibre dispersion: Fibres were dispersed manually in small quantities during mixing until they were fully integrated into the mix.
- Mixing time: Mixing time for BFRC was increased by 90 seconds to ensure formation of a homogeneous composite.

Workability Tests:

Tests on fresh concrete were conducted to ensure adherence to research quality requirements. The checks that were done include: slump, ambient temperature and concrete temperature measurements and were carried out in accordance with ASTM C143/C143M-20, (2020). Moulds smeared with oil were filled with concrete using a scoop in layers and then vibrated in accordance with BS EN 12390-2, (2019).

Finishing of the top face of the cast samples in the moulds was done concurrently with vibration to ensure that fibres do not protrude through the finished surface.

Curing

After 24 hours, samples were de-moulded and immersed in a curing tank. Curing was done in accordance with (ASTM C31/C31M-19, 2019).

3.7 Mechanical Testing

3.7.1 Precautions taken during tests

Calibration of Test equipment reliability: The test equipment were checked to ensure that they had the latest calibration certificates and that all systems were in good working conditions, that is, bearing surfaces were clean from any foreign material like loose grits or other extraneous materials.

3.7.2 Test Parameters with corresponding standards

Table 3.12: Summary of the tested parameters

Test Parameter	Standard
Compressive Strength	BS EN 12390-3 (2009)
Flexural strength	ASTM C293/C293M-16 (2016)
Split Tensile strength	ASTM C496/C496M–17 (2017)
Microstructure	ASTM C1723-16 (2016)

3.7.3 Compressive strength

Test Procedure

The Test was performed in accordance with the standard testing procedures prescribed in BS EN 12390-3 (2009). Universal Testing Machine (UTM) of 3000 kN maximum capacity was used. Standard cubes with dimensions 150 mm conforming to BS EN 12390-1 (2012), were tested at 14 and 28 days. Samples were tested with the loading rate maintained within the range of 0.6 ± 0.2 MPa/s, corresponding to 9 ~ 18 kN/s. The maximum load at failure was recorded (kN) and used to calculate the compressive strength of concrete using equation 3.3.

$f_c = \left(\frac{P}{bd}\right)$ .... Equation 3.3;

Where; f_c- Compressive cube strength (N/mm^2) ; P- Peak load (N), b- width, and d - depth; all in mm.

3.7.4 Split Tensile Strength Test

Figure 3.7 shows the modified compression testing machine used to test Split Tensile Strength Test.

Figure 3.7: Test for Split tensile strength

This Test was carried out as per the standard test procedure prescribed in ASTM C496/C496M–17 (2017). The same UTM that was used during compressive strength test was used to determine the split tensile strength of the cylinder samples. However, the bearing surfaces of this UTM were made of square dimension equivalent to 200 mm yet the dimensions of the cylinder samples were of length 300 mm and diameter 200 mm. Therefore, in order to fit the testing machine, two steel plates of similar dimensions $(400 \times 200 \times 50)$ mm were added at the top and bottom of the existing bearing plates.

Rate of Loading: The loading rate was applied and maintained in the range of 0.7 to 1.4 MPa/min until failure of the sample. Samples at the age of 14 days were tested normally. In order to determine the ultimate load and residual strength that could be sustained by the fibres, samples were subjected to loading and unloading (cyclic loading) testing till failure. The corresponding loads were recorded, and used to determine ultimate split tensile strength and the corresponding residual strength of samples using equation 3.4.

$$T = \left(\frac{2P\ (kN)}{\pi l d\ (mm^2)}\right) \text{..............Equation.3.4}$$

where; T- Split tensile strength (N/mm^2) ; P- failure load (N), l- length, d- diameter, all in mm.

3.7.5 Flexural strength Test- Beam with Third-Point Loading

Figure 3.8: Test setup for Flexural strength test

To determine the flexural strength of plain and Banana fibre reinforced concrete, beam samples with dimensions (mm) $150 \times 150 \times 350$ were tested under third point loading. The flexural strength test protocol was in accordance with the test procedures provided in (ASTM C293/C293M-16, 2016). The Universal Testing Machine of 2500 kN capacity was used to determine the peak load at failure of the sample as shown in Figures 3.7 and 3.8. The peak load obtained at failure was used to calculate the flexural strength of beam samples using equation 3.5:

$$f = \left(\frac{3PL)}{2bd^2}\right) \text{................Equation. 3.5;}$$

Where; f- Flexural strength (N/mm^2) ; P is the peak load (N); L- span (300 mm), b-width, and, d- beam depth; all in mm.

3.8 Microstructural Characterization and Microanalysis

3.8.1 Introduction

ASTM C1723-16 (2016) provides guidelines on the microstructural features of concrete which include, size and shape of individual constituents (including pores), the spatial relationships between constituents and volume fraction of each constituent.

3.8.2 Scanning Electron Microscopy (SEM)

To determine the morphology of the Plain and Banana fibre reinforced concrete, samples were investigated under a Variable Pressure Scanning Electron Microscope (VPSEM), Model: Tescan Vegas- 3; and XRD machine. Figure 3.9 shows the VPSEM equipment.

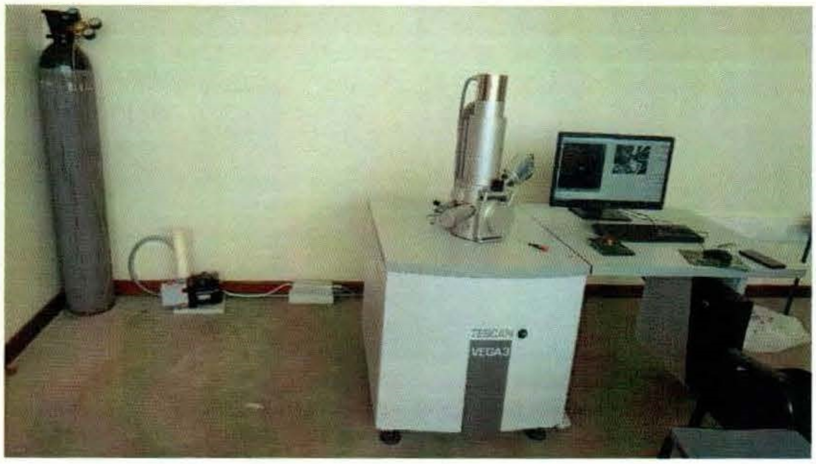


Figure 3.9: Scanning Electron Microscope

a) Materials and Features

Samples were analysed at the age of 28 days and morphological features, i.e. cracks and Voids within the composite, Paste-aggregate ITZ; according to the standard, concrete ITZ is typically about 50 µm. Examination was carried out to determine the change in the ITZ between bulk Paste-aggregate-fibre composite. Deposition of unreacted components (residual Portland cement particles).

b) Sample Preparation

The procedure followed in sample preparation were in accordance with ASTM- C856-95 (1998) and ASTM C1723-16 (2016). Samples were sectioned to 10 mm square size in order to fit on the sample holder of the SEM. The sectioned samples were then cleaned to remove any external material that could interfere with image processing and recording. Figure 3.10 shows the sectioning process of the samples.

Figure 3.10: Sample preparation for SEM

c) Sample Examination under the SEM

Sample examination was carried out to determine the general morphology of the sample (change in the ITZ (refer to section 3.8.2 (a) between bulk paste-aggregate-fibre composite and deposition of unreacted components (residual Portland cement particles)). The SEM was adjusted and operated under the following input parameters: Detector: Secondary Electron (SE); 15.0kV accelerating voltage; working distance: 15.

3.8.3 Energy Dispersive X-ray Spectroscopy (EDS/XRD

Figure 3.11: XRD Equipment

Samples of Plain concrete and FRC were crushed into powder and investigated under the Energy Dispersive X-ray Spectroscopy (EDS/XRD) machine for identification of phases within the composite (shown in Figure 3.11). XRD generally comprises the energy-dispersive detector coupled with wavelength detector. The energy-dispersive detector collects the entire spectrum within the sample, while the wavelength detector acquires the spectrum sequentially. The generated data are displayed as strength (intensity in counts) corresponding to the position (angle). The collected data were later plotted using Excel, a computer database program to generate micrographs with differing relative peak intensities which were later analysed to identify phases within the composite. The positions of the peaks are characteristic of a particular element, identifications were made by examination of peak positions and relative intensities.

3.9 Finite Element Modelling of the Behaviour of BFRC and Plain Concrete

3.9.1 3D Representative Volume Element, RVE, Model

The concept of Homogenization Technique of 3D Representative Volume Element (RVE) was applied in Finite Element Analysis to model the behaviour of Banana Fibres in Concrete. ABAQUS^{TM} version 6.14 computer software was used in the modeling. The selection of the 3D RVE Model was based on the work presented by Barbero, (2008) and, Mobasher, (2012).

3.9.2 Purpose of the Model

The purpose of modelling in ABAQUS computer software was to determine the behaviour of Banana fibre reinforced concrete and plain concrete by using applicable failure theories (like the von mises and maximum principal stress theories) that allow to predict the failure of a material by comparing the stress state in the material being assessed with material properties experimentally determined under uniaxial tension or compressional loading conditions.

3.9.3 Assumptions of Banana fibre reinforced Concrete Model

- Fibres are embedded in an elastic mixture,
- Fibres are cylindrical and randomly distributed, with a random microstructure forming a hexagonal arrangement as shown in Figure 3.12.
- Fibres are Anisotropic; the elastic modulus in the X, Y, and Z directions are different,
- There exists a strong bond between matrix and fibre,
- The distance between fibres and matrix is short hence increased ability to allow load sharing between fibres and the matrix.

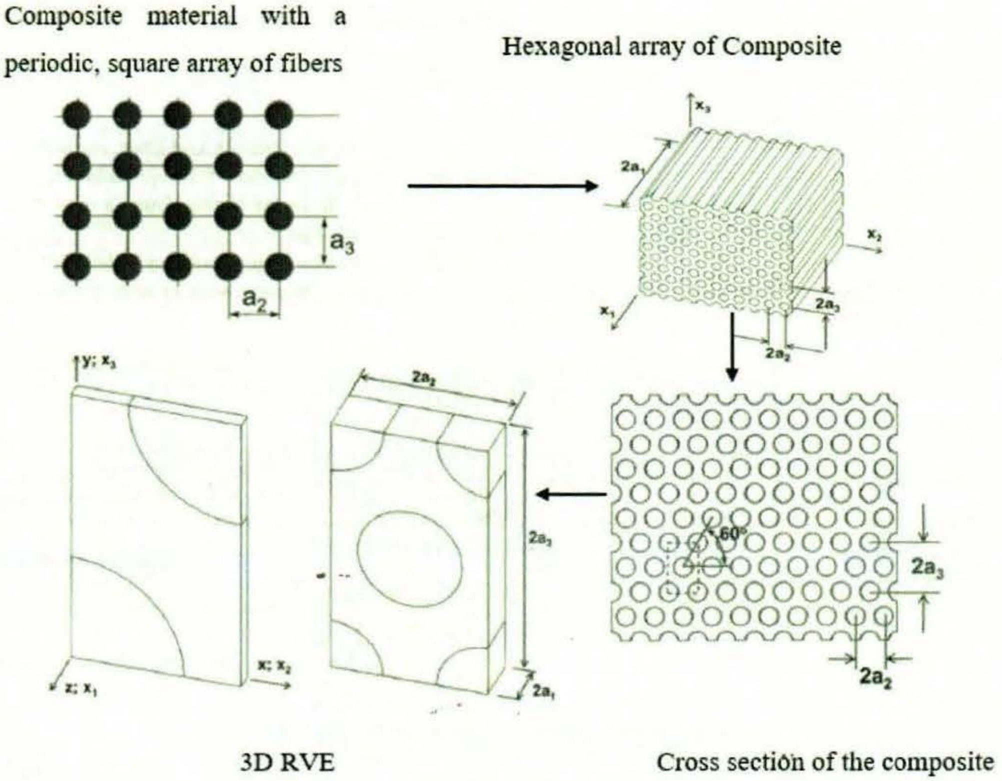


Figure 3.12: Formation of the 3D RVE, (Barbero, 2008)

3.9.4 Determination of the RVE Size

- Average fibre diameter = 102.82 μm
- Volume fraction of fibres; $V_f = \frac{v_f}{v_c} = \frac{4a_1\pi\left(\frac{d_f}{2}\right)^2}{2a_1 \times 2a_2 \times 2a_3}$
- The relation between a_2 and a_3 was established by the hexagonal array pattern, implying $a_3 = a_2 tan60$ (Barbero, 2008).
- The optimum fibre length of 40 mm and 0.10 % fibre content were selected to model the behaviour of the fibres in concrete.
- The calculated size of the RVE are shown in Table 3.13.

Table 3.13: Size of RVE (40 mm fibre length and 0.10 % fibre content)

Fibre diameter	V_f	Hexagonal size of RVE, μm		
		2a1	2a2	2a3
102.82 μm	0.10 %	77.43	309.70	536.42

3.9.5 Material properties and modeling

Based on the assumptions, linear elasticity associated with the material principal directions was defined by Engineering Constants (Elastic moduli, E11, E22 and E3; Poisson's ratios, ν_{12}, ν_{13}, ν_{23} and Shear moduli, G_{12}, G_{13}, G_{23}). Computation of the engineering constants was done using PMME.xls (Barbero, 2008). Table 3.14 shows the calculated engineering constants that were used in ABAQUS model.

Table 3.14: Engineering constants used in the FEM RVE Model

PMM micromechanics, isotropic fibre, elastic matrix						
Fibre content	0.10%	2.50 %				
Matrix- concrete	Elastic Modulus, E_m (GPa)				30 (EC2)	
	Poissons ratio, ν_m				0.2	
Fibre- Banana Fibres	Elastic Modulus, E_f (GPa)				3.48	
	Poissons ratio, ν_f				0.3	
Computed Engineering constants						
Fibre content	E1	E2= E3	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$	G_{23}
0.10 %	29.974	29.939	0.200	0.200	12.480	12.472
2.50 %	29.340	28.523	0.201	0.207	12.011	11.819

3.9.6 Analysis type

The selection of analysis type is the very first step in any FEA work. The various analysis types are structural analysis, thermal analysis, fluid analysis, heat transfer analysis, electromagnetic analysis, buckling analysis, electrical analysis, and multiphysics analysis. For this research the RVE modelled under structural static analysis was used.

3.9.7 Boundary Conditions

The model was subjected to encastre boundary condition where U1=U2=U3=UR1=UR2=UR3= 0. The aim was to constrain its movement during load application and determine the resulting deformation from the applied uniaxial pressure loads.

3.9.8 Loading

Uniaxial Tension and compression pressure loads were defined and applied. The design ultimate strength of concrete was C20/25. For compression, 12 MPa and 17 MPa was applied, while for tension, 1.05 MPa and 1.5 MPa was applied.

3.9.9 Solution

After all the preprocessing works of FEA of the FRC, the database file was then solved in a finite element solver. After successful solving the finite element model, results were then extracted from the solution model and presented in the following chapter.

CHAPTER- 4 : RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents, the results from the experiments undertaken to investigate the effect of Banana fibres on the mechanical and microstructural properties of concrete. To accurately interpret and describe data in order to come-up with meaningful insights; statistical techniques were applied. The SEM images were also investigated and used to describe the morphology of the samples. XRD data obtained were plotted in Excel and analysed to identify the changes in phases within the composite. ABAQUS, a finite element analysis computer software, was used to analyse the micromechanical (3D RVE) model.

4.2 Presentation and Analysis of Results

4.2.1 Geometric, physical and strength properties of Banana fibres

The following Table 4.1, presents a summary of the Geometric, physical and strength properties of Banana fibres test results of Banana fibres obtained using an Electronic Single Fibre Strength Tester, and some in Appendix Table B1.

Table 4.1: Geometric, physical and strength properties of Banana fibres

Fibre Parameter	**Property**
Stiffness, (mm)	56.8
Weight, (g)	56.8
Linear mass density, g/m	1953
Diameter, µm	102.82
Breaking Strength, (gf)	142.17
Breaking Elongation, (%)	3.22
Tensile Strength for a Single Banana Fibre, MPa	167.89
$1\ gf = 0.001 \times 9.81 = 0.00981 kgm/s^2$=1N	
Tensile strength= $142.17 \times 0.00981/(0.25\pi \times 0.10282)$	

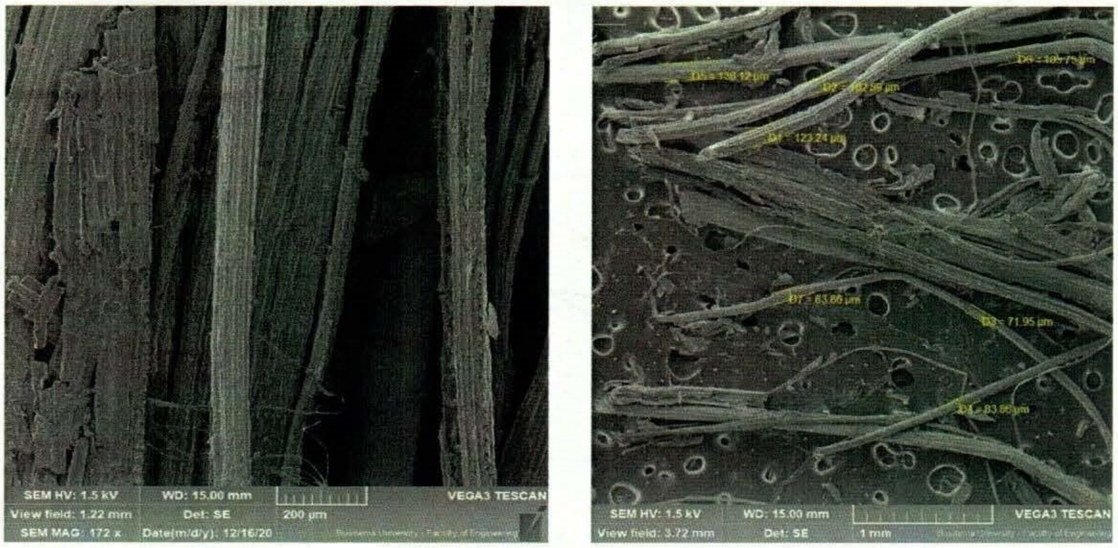


Figure 4.1: SEM Micrographs-Banana Fibre Microstructure and Fibre Diameter

4.2.2 Compressive strength

a) Compressive strength of concrete at 14 days

Figure, 4.2 presents the effect of varying fibre length and fibre content on the compressive strength of concrete samples containing plain concrete (reference concrete) and Banana fibre reinforced concrete at 14 days.

Test results for fibre length (40, 50 and 60 mm) and the corresponding fibre content (0.1 %, 0.25 %, 1.00 %, 1.50 % and 2.5 %) are presented in Table B2 of Appendix B2. The Table further shows the following parameters; mean strength, minimum and maximum strength; standard deviation, Coefficient of Variation and Correlation coefficients for both plain concrete and Banana fibre reinforced concrete. The following observations were drawn;

For 40 mm and 60 mm fibre length, the corresponding fibre content of up to 1.00 % resulted in the mean compressive strength that was higher than that of the reference concrete. It is seen that the strength increases as the fibre content reduces from 2.5 %, 1.50 %, 1.00 %, 0.25 % to 0.10 %. The compressive strength was significantly lower than that obtained for plain concrete at 1.50 % and 2.50 % fibre contents.

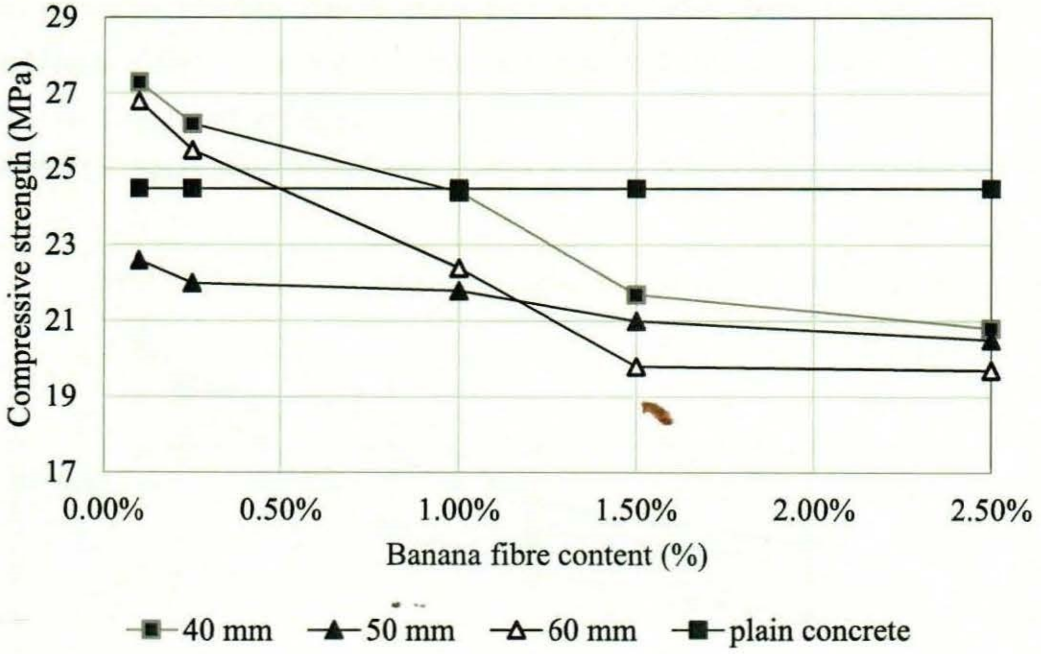


Figure 4.2: Effect of fibre content on compressive strength of concrete at 14 days

For 50 mm fibre length: all fibre contents resulted in the mean compressive strength that was lower than that of plain concrete. Similarly, the strength increases as the fibre content reduce from 2.5 %, 1.50 %, 1.00 %, 0.25 % to 0.10 %. There was a general indirect correlation between fibre content, fibre length and compressive strength implying that higher fibre length and fibre content negatively affected the rate of strength development. The maximum increase in strength attained compared to plain concrete (reference concrete) at 14 days was 11.4 %; corresponding to 40 mm fibre length and 0.10 % fibre content.

b) Compressive strength of concrete at 28 days

Figure 4.3 that follows presents the effect of varying fibre length and fibre content on the compressive strength of concrete samples containing plain concrete (reference concrete) and Banana fibre reinforced concrete at 28 days. Similarly, test results for fibre length (40, 50 and 60 mm) and the corresponding fibre content (0.1 %, 0.25 %, 1.00 %, 1.50 % and 2.5 %) are presented in Table B2 of Appendix B2.

The figure in addition shows error bars that express potential error amounts graphically relative to each data point within the experimental data series. N- values were also determined to forecast the trend as fibre content and length parameters were varied. The values depict a further reduction in strength with increase in fibre content.

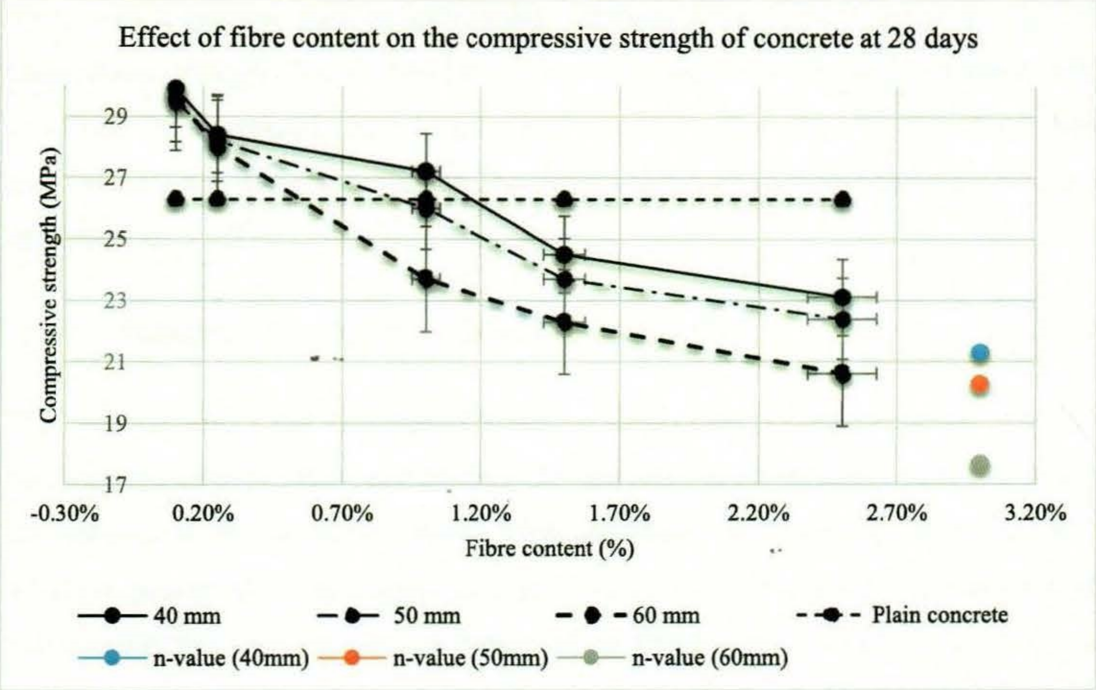


Figure 4.3: Effect of fibre content on compressive strength of concrete at 28 days

The Table further shows the following parameters; mean strength, minimum and maximum strength; standard deviation, Coefficient of Variation and Correlation coefficients for both plain concrete and Banana fibre reinforced concrete.

It is observed that for 40 mm and 50 mm fibre length; fibre content of up to 1.00 % resulted in the mean compressive strength that was higher than that of the reference concrete. It is seen that the strength increases as the fibre content reduces from 2.5, 1.50 %, 1.00 %, 0.25 % to 0.10 %. The compressive strength was significantly lower than that obtained from plain concrete for 1.50 % and 2.50 % fibre contents.

For 60 mm fibre length: Fibre contents of 0.10 % and 0.25 % resulted in the mean compressive strength that was higher than that of plain concrete. Similarly, the strength increases as the fibre content reduces from 2.5 %, 1.50 %, 1.00 %, 0.25 % to 0.10 %.

The compressive strength was significantly lower than that obtained from plain concrete for 1.00 %, 1.50 % and 2.50 % fibre content.

The maximum increase in strength attained compared to plain concrete (reference concrete) was 12 %; corresponding to 40 mm fibre length and 0.10 % fibre content. There was a general indirect correlation between fibre content, fibre length and compressive strength. The Coefficient of Variation (CV) and Standard Deviation (SD) increased with increase in fibre length. Implying that higher fibre length make results more volatile and dispersed. Higher fibre length and fibre content negatively affected the rate of strength development.

c) Discussion of Compressive Strength Test results

The results for plain concrete (reference concrete) revealed normal strength development obtained at 14 and 28 days. The increase in compressive strengths due to the inclusion of Banana fibres, can be attributed to the reinforcing action of the fibres which improved the compressive strength, where the loads generated were shared between the fibres and concrete, as presented by Zhang *et al* (2018). Similar results on compressive strength were reported by Mukhopadhyay & Bhattacharjee (2016, Chandramouli *et al* (2019), Dhawan *et al* (2020) and Humphrey (2020). Conversely, the reduction in compressive strength with increasing fibre length and fibre content can be attributed to balling effect which occurred during manual inclusion of fibres at the time of mixing which resulted in their non-uniform distribution within the mix. This interfered with strength development and resulted in stress localization. A study by Mukhopadhyay & Bhattacharjee (2016) reported on the clustering of fibres in isolated sections within the mix. Pederneiras *et al* cited in Humphrey (2020), associated the reduced compressive strength to the large quantity of fibres in the mortar which produced voids and created non-uniform distribution within the composite. The obtained results agree with the results previously obtained by a number of scholars (Ellen *et al,* 2018; Prasannan *et al*, 2018; Elbhiery *et al*, 2020; Dhawan *et al*, 2020).

4.2.3 Flexural strength

a) Flexural strength of Concrete at 14 days

In this study, the flexural strength for plain concrete (reference test) and Banana fibre reinforced concrete was determined. Figure 4.5 presents the effect of varying fibre length and fibre content on the Flexural strength of concrete samples containing plain concrete (reference concrete) and Banana fibre reinforced concrete at 14 days. Test results for fibre content (0.1 %, 0.25 %, 1.00 %, 1.50 % and 2.5 %) and fibre length (40, 50 and 60 mm), at 14 and 28 days are presented in Table B3 of Appendix B2. The Table further shows the following parameters: mean strength, minimum and maximum strength; standard deviation, Coefficient of Variation and Correlation coefficients for both plain concrete and Banana fibre reinforced concrete. The following observations and conclusions were made for each fibre length and the corresponding fibre content.

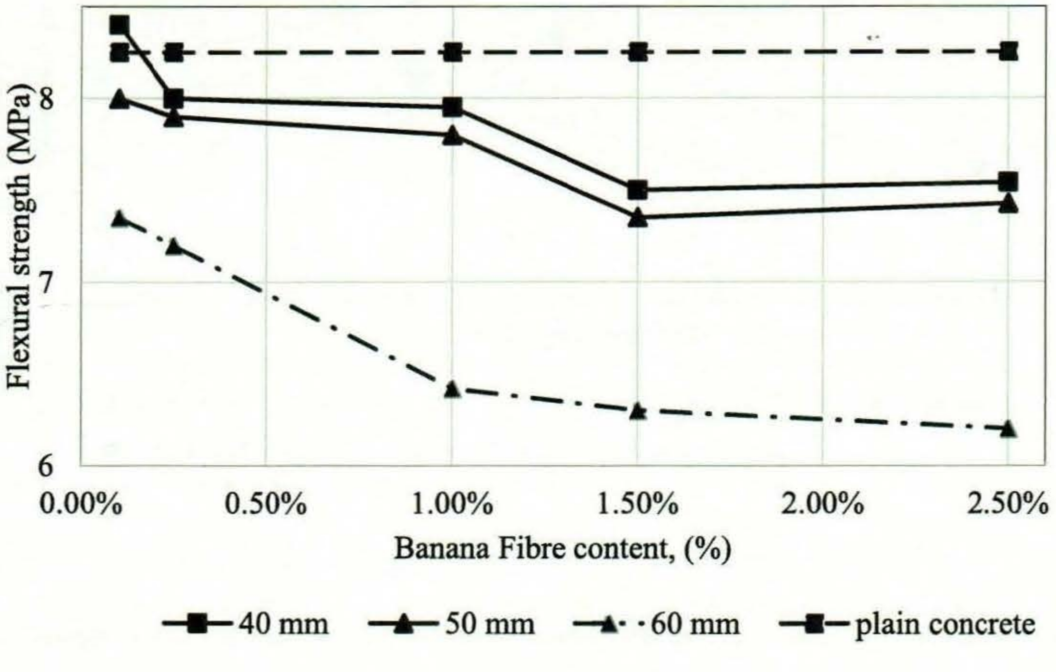


Figure 4.4: Effect of fibre content on Flexural strength of concrete at 14 days

It is observed that for 40 mm fibre length; only fibre content of 0.10 % resulted in the mean flexural strength that was higher than that of the reference concrete. The remaining values of the fibre contents were the values of the reference concrete. The maximum increase in flexural strength was 1.82 % corresponding with 0.10 %. The strength increases as the fibre content reduces from 2.5 %, 1.50 %, 1.00 %, 0.25 % to 0.10 %. The flexural strength was significantly lower than that obtained from the reference concrete for 2.50 % fibre content and 60 mm fibre length implying that the rate of strength development was negatively affected. There was a general indirect correlation between fibre content, fibre length and flexural strength. The maximum increase in strength attained compared to plain concrete (reference concrete) was 1.82 %; corresponding to 40 mm fibre length and 0.10 % fibre content.

b) Flexural strength of concrete at 28 days

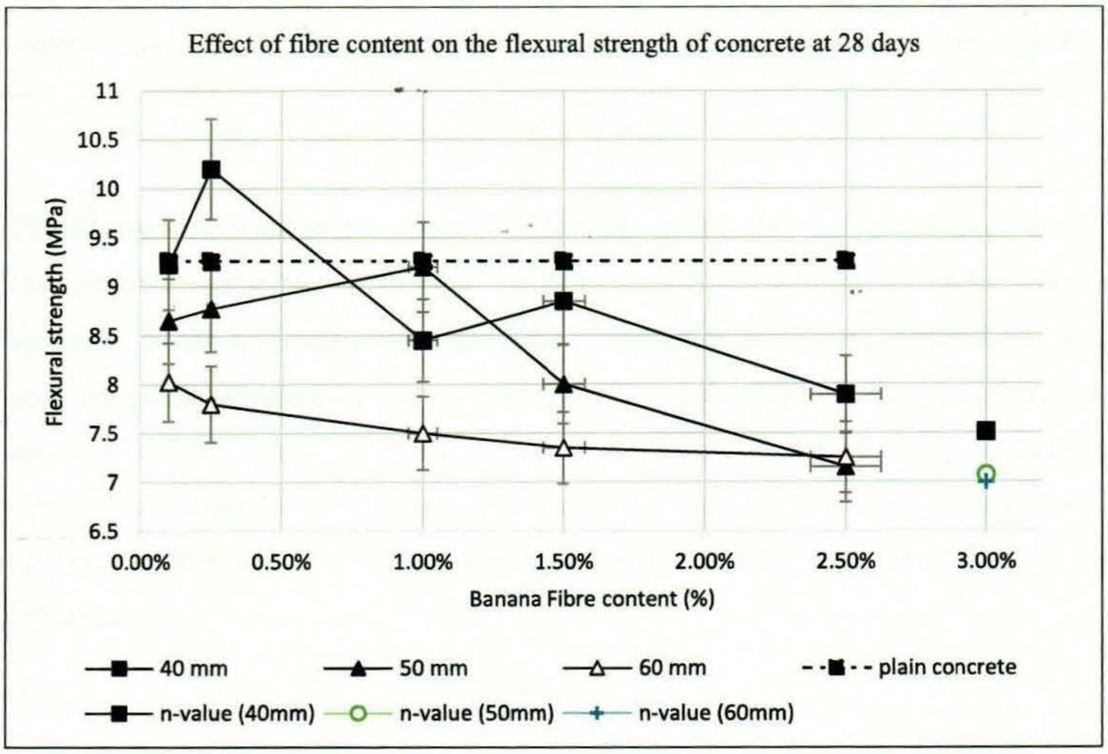


Figure 4.5: Effect of fibre content on Flexural strength of concrete at 28 days

Findings in Figure 4.5 reveal that the Flexural strength test results for Banana fibres containing 40 mm length corresponding with 0.10 % fibre content exhibited higher test results than the test results of the reference concrete; implying that the inclusion of fibres in concrete resulted in an improvement in the Flexural strength of concrete. Conversely, the results of the remaining samples were the results of the reference concrete, as demonstrated by an indirect correlation between the fibres and the flexural strength of concrete. This implies that increasing fibre content and fibre length, negatively affected the flexural strength of concrete. Considering dispersion and variability of the samples, 60 mm fibre length produced results that were more dispersed and volatile than the rest of the samples. Therefore, it can be concluded that, 40 mm fibre length and 0.10 % fibre content improved the flexural strength of concrete at 28 days.

The figure in addition shows error bars that express potential error amounts graphically relative to each data point within the experimental data series. N- values were also determined to forecast the trend as fibre content and length parameters were varied. The values depict a further reduction in strength with increase in fibre content.

c) Discussion of Flexural Strength Test results

The Flexural strength test results revealed both an increase and a reduction in the strength obtained at 14 and 28 days. First, the increase in strength for BFRC can be attributed to the bridging capability of the fibres when cracks are initiated and this prevents crack propagation due to sharing and/or redistribution of stresses between matrix and fibres, hence improving on toughness of concrete after cracking (Mobasher, 2012). The obtained results are consistent with the results obtained by Tehmina *et al* (2014), Chandramouli *et al (*2019) and Dhawan *et al (*2020) that were carried out on Banana fibres.

Conversely, some test results revealed a reduction in the flexural strength with increasing fibre length and fibre content. This can similarly be attributed to the difficulty during experimentation especially at the time of dispersion of fibres during the mixing process where the fibres were manually dispersed in concrete in small quantities during mixing. Whereas thorough mixing was done, fibres were not uniformly dispersed and this effect was identified during sample examination after the testing process. This is considered a general challenge encountered during mixing and was also reported by Mukhopadhyay & Bhattacharjee (2016). The results corroborate the findings obtained earlier by other rearchers (Ellen *et al*, 2018; Prasannan *et al*, 2018; Elbhiery *et al*, 2020; Dhawan *et al*, 2020).

4.2.4 Split Tensile Strength

a) Split Tensile Strength of Concrete at 14 days

Figure 4.7 present the trends of varying fibre length and fibre content with Split tensile strength. The results for plain concrete (reference test) and Banana fibre reinforced concrete is included in Table B4 and B5 in Appendix B

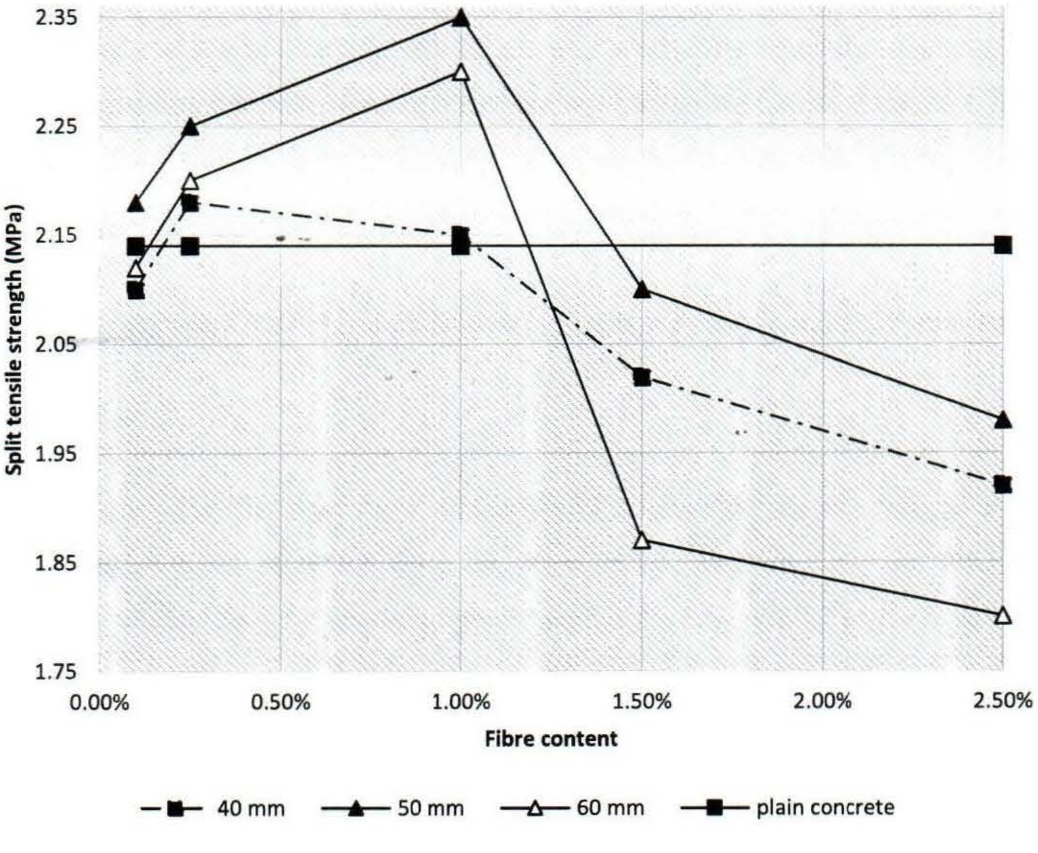


Figure 4.6: Effect of fibre content on Split tensile strength of concrete at 14 days

The findings from Figure 4.7, revealed that all fibre length at 0.25 % and 1.00 % fibre contents resulted in the mean Split tensile strength that was higher than that of the reference concrete. 50 mm and 60 mm Fibre length had their peak length at 1.00 %; while 40 mm length exhibited its peak strength at 0.25 %. The Split tensile strength was significantly lower than that obtained from plain concrete for all the fibre contents. There was a general indirect correlation between fibre content, fibre length and compressive strength. The maximum increase in strength attained compared to the reference concrete was 9.8 %; corresponding to 50 mm fibre length and 1.00 % fibre content.

b) Split Tensile Strength of Concrete at 28 days

In this study, the results for Split Tensile strength for plain concrete (reference test) and Banana fibre reinforced concrete containing fibre content (0.1 %, 0.25 %, 1.00 %, 1.50 % and 2.5 %) and fibre length (40, 50 and 60 mm) at 28 days are presented. The ultimate load and residual strength of the samples were determined by subjecting the samples to loading and unloading (cyclic loading) testing till failure. Figures 4.7 and 4.8 present the Effect of different loading cycles on the residual split tensile strength of concrete. Table B5 of Appendix B2 presents the Split tensile strength test results corresponding to the loading cycles. Based on Figure 4.7, the following observations and conclusions were made for each fibre length and the corresponding fibre content.

Observations

The four loading cycles that were diametrically applied during the testing of the samples revealed the effect of fibre inclusion in concrete as compared to plain concrete. All the loading cycles were applied within the range of 0.7 to 1.4 MPa/min.

The 1st loading cycle resulted in ultimate split tensile strength for both plain concrete (reference concrete) and Banana fibre reinforced concrete containing 40 mm, 50 mm and 60 mm fibre length and their corresponding fibre content. However, the following loading cycles revealed different behaviour for both plain concrete (reference concrete) and Banana fibre reinforced concrete as follows.

Banana fibre reinforced concrete: The sample was examined the 1st loading cycle and no cracks were visible. The loading cycles was then increased to 2nd, 3rd and 4th loading cycles and the following observations were made. It was observed that increase in loading cycles up to the 3rd cycle resulted in progressive reduction in split tensile strength to the lowest strength coupled with the formation of hairy cracks which propagated parallel to the direction of load application. When the 4th loading cycle was applied, an increase in the load at failure corresponding to the failure strength was observed coupled with the increase in the size of the formed cracks. The fibres were observed bridging the cracks and thereby prevented the sample from splitting.

While for plain concrete: The increase in loading cycles up to the 4th cycle resulted in progressive reduction in split tensile strength and the formation of more than one crack which propagated in different directions.

For BFRC, considering 40 mm fibre length and 0.10 % fibre content, the residual strength obtained with the 4th loading cycle was up to 1.41 MPa from 1.02 MPa (equivalent to 38 %); while plain concrete did not exhibit any increase in strength with increase in loading cycles.

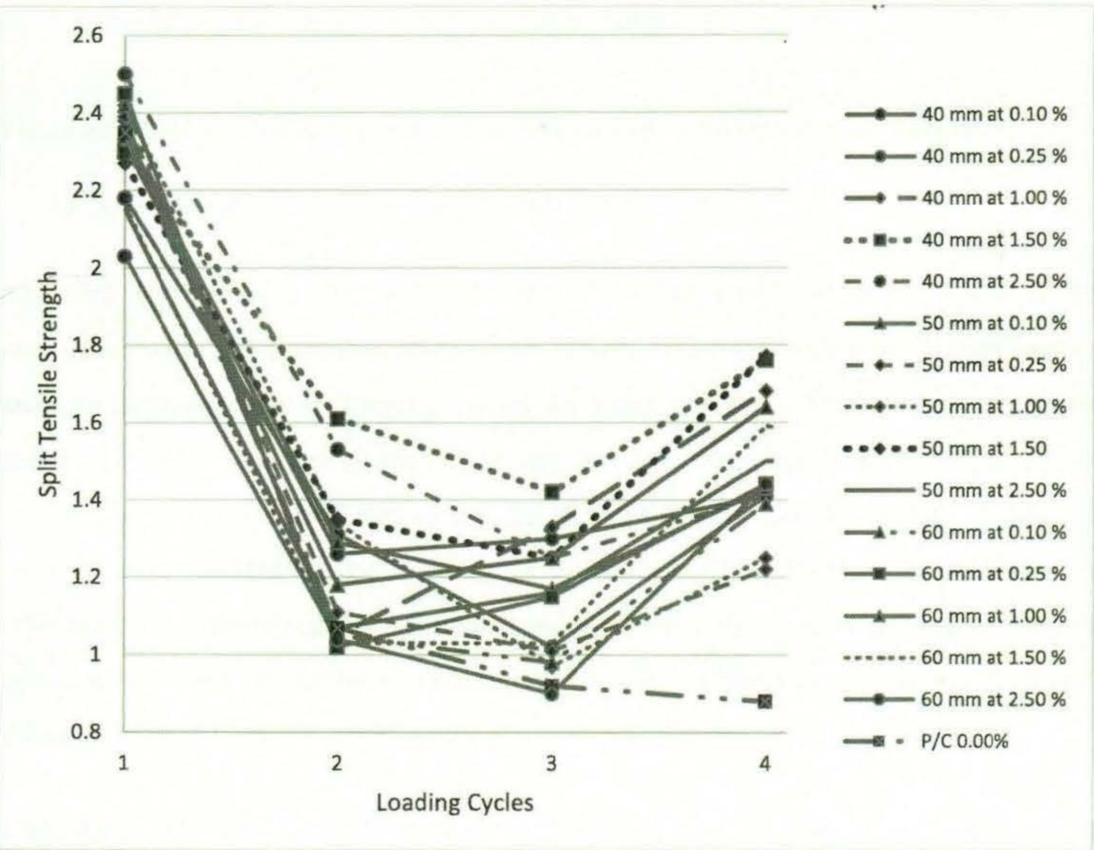


Figure 4.7: Residual Strength of all Concrete samples at varying loading cycles

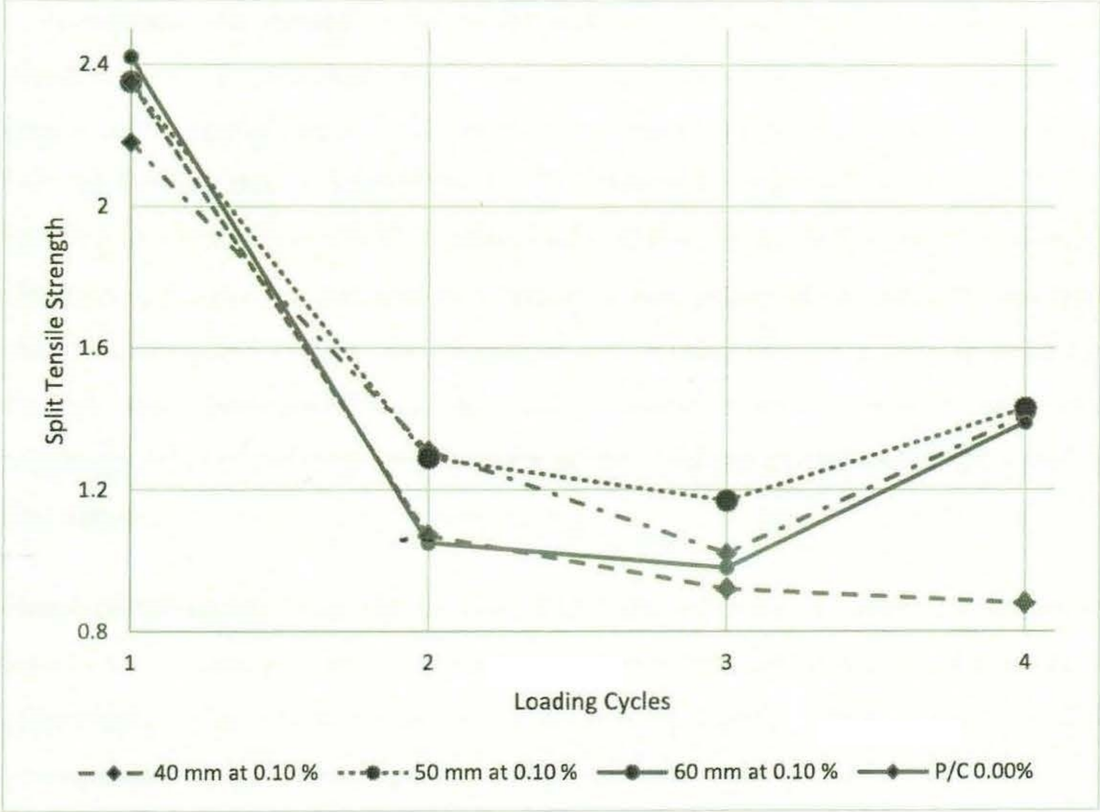


Figure 4.8: Residual Strength of Concrete at varying loading cycles at 0.10 % Fibre content

c) Discussion of Split Tensile Strength Test results

The first peak strength obtained under the 1st loading cycle can be attributed to the normal strength development of concrete. There was total reduction in split tensile strength with increase in loading cycles for plain concrete. This behaviour can be ascribed to the inadequate elastic behaviour, low toughness, and lack of friction within the matrix which occurred due to the initiation of cracks that propagated within the concrete and resulted in the splitting of the sample. This typical observation was reported by Humphrey (2020). The obtained results are also consistent with the results obtained by other researchers (Tehmina *et al,* 2014, Chandramouli *et al*, 2019 and Dhawan *et al*, 2020).

Conversely for BFRC, there was both reduction and increase in strength which occurred after formation of cracks. The reduction can be attributed to the performance of normal concrete without fibres that is characterised by the lack of elastic behaviour, low toughness, and limited friction of the matrix. After crack formation, the presence of fibres inside the concrete matrix were activated and therefore bridged across the cracks and prevented further crack opening, expansion and propagation by sharing the induced stresses due to applied loads. This therefore prevented the samples from splitting as observed at the 4th loading cycle where the residual strength increased (Mobasher, 2012). The presence of fibres improved ability of the concrete and was able to restrict and reduce the generation and development of cracks in concrete through fibre bridging. Fibres provided adequate elastic behaviour, enhanced toughness index of concrete by increasing on the residual strength and friction within the matrix.

Based on the results, it can be concluded that the inclusion of fibres in concrete at lower fibre content and fibre length can improve the residual strength and toughness of concrete after crack initiation by preventing against crack expansion and propagation thereby increasing the resilience and service life of concrete.

4.2.5 Results from the Microstructure of Plain and FRC

a) SEM

The following Figures 4.15 and 4.16 show the morphology of plain concrete and Banana FRC under the Scanning Electron Microscope.

Figure 4.9: SEM - Plain concrete

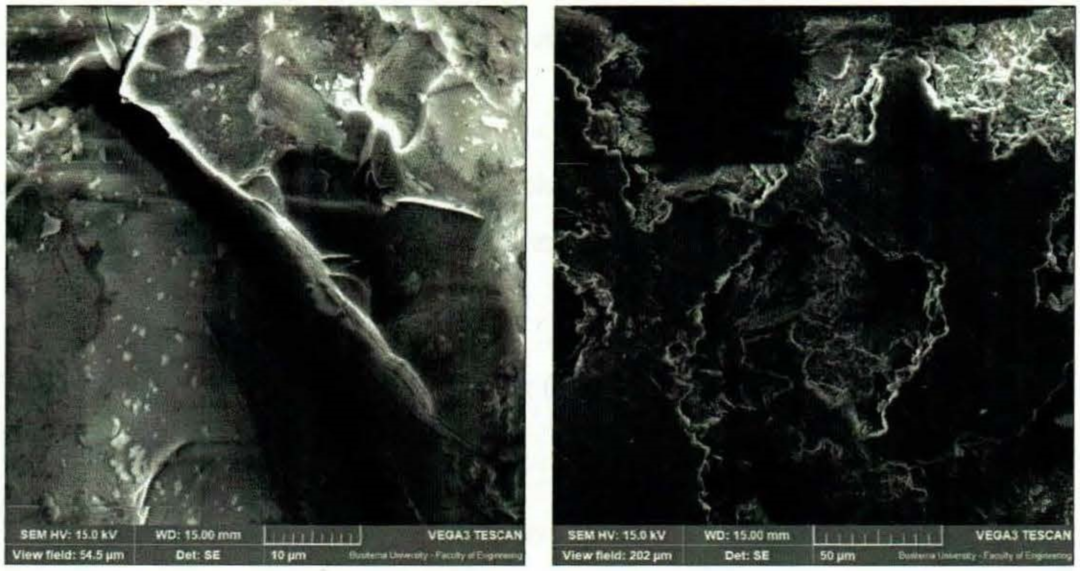


Figure 4.10: SEM FRC Morphology

The following observations were drawn out of the SEM images:

In figure 4.8, plain concrete demonstrates a porous morphology with varying sizes. It exhibited normal setting, the ITZ was identified between bulk Paste-aggregate-fibre composite. Cracks and voids within the composite were not seen

For FRC (Figure 4.9): Figure reveal that; Larger rectangular voids or pores were observed with defined boundaries. A clear transition zone exists within concrete and fibres.

b) Discussion of the SEM Test Results

In Figure 4.8, it can be noticed that the high porosity observed, can be attributed to the initial water absorption which affected the rate of hydration. The results obtained are similar to the findings from other scholars (Sivaraja *et al*, 2010)

c) Energy Dispersive X-ray Spectroscopy (EDS/XRD

Figures 4.10 ~ 4.13 show micrographs of Banana fibre reinforced concrete and Plain concrete samples at different diffraction angles and intensities appearing as peaks,

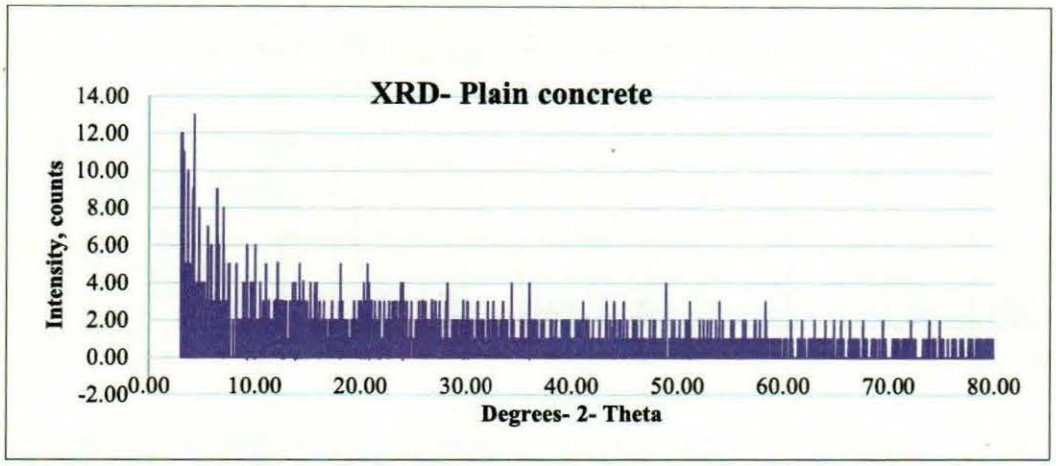


Figure 4.11: XRD- Micrographs for Plain concrete

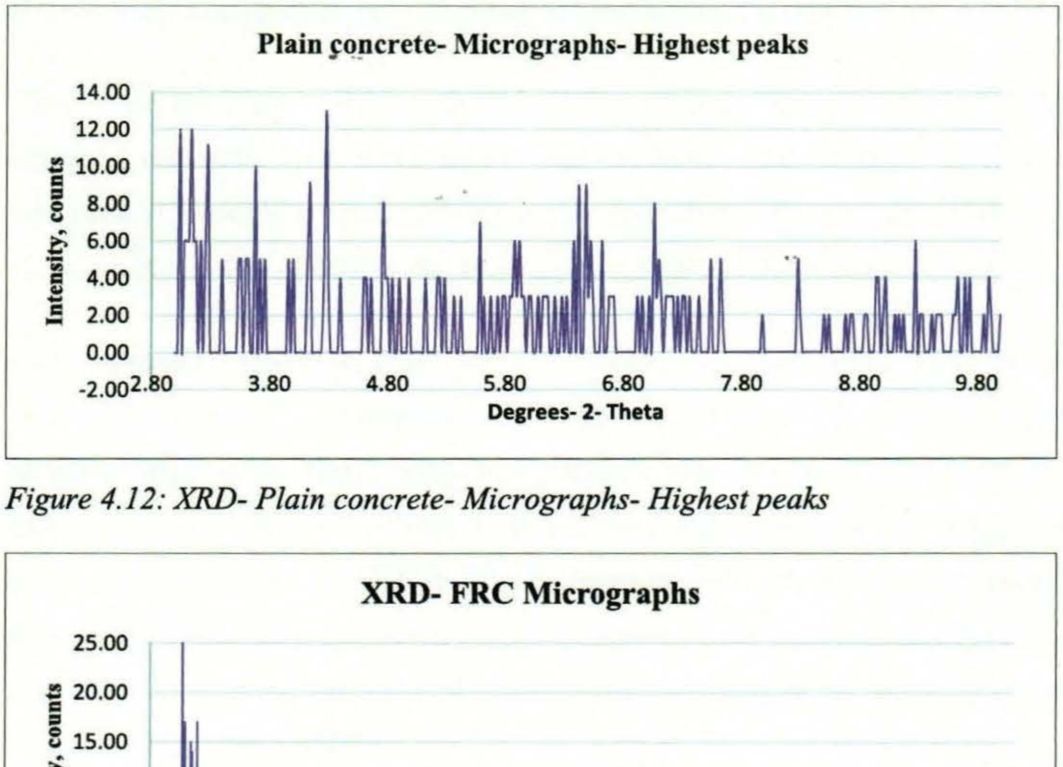


Figure 4.12: XRD- Plain concrete- Micrographs- Highest peaks

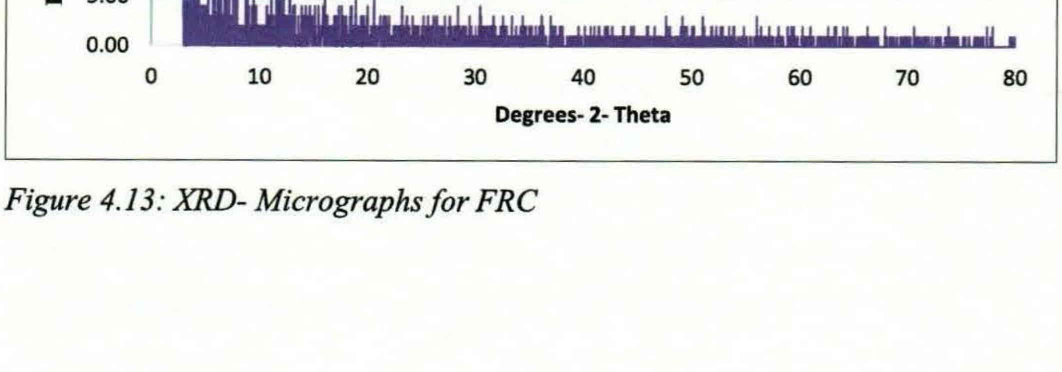


Figure 4.13: XRD- Micrographs for FRC

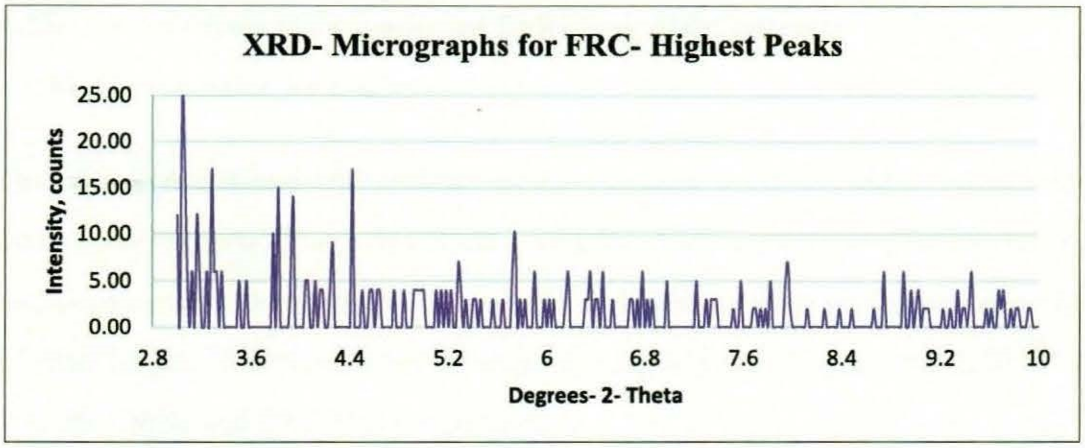


Figure 4.14: XRD- Micrographs for FRC- Highest Peaks

Based on the micrographs, the following observations were drawn:

Plain concrete Figures 4.11 and 4.12: Different peaks were obtained at different positions combined with sharp peaks. The maximum peak intensity is 13 counts occurring at an angle (2θ) of 4.28, other corresponding peaks include; (3.04, 12.00), (3.14, 12.00), (3.28, 11.00), (3.68, 10.00), (4.14, 9.00), (6.42, 9.00).

FRC Figures 4.3 and 4.14: Different peaks were obtained at different positions Sharp peaks were observed. The maximum peak has an intensity of 25 counts occurring at an angle (2θ) of 3.04, other corresponding peaks include; (3.00, 12.00), (3.06, 18.00), (3.16, 12.00), (3.28, 17.00), (3.82, 15.00), (3.94, 14.00), (4.26, 9.00), (4.42, 17.00), (5.72, 7.00), (5.74, 10.00). FRC had the highest peak intensity of 25 counts occurring at an angle (2θ) of 3.04, compared to plain concrete whose peak intensity is 13 counts occurring at an angle (2θ) of 4.28. There were variations in the shape of the peak intensities that were obtained

d) Energy Dispersive X-ray Spectroscopy (EDS/XRD)

Analysis of results under the Energy Dispersive X-ray spectroscopy (EDS) reveal the following; The higher peak intensities at a lower position (angle) indicate maximum interplanar spacing within the crystal structure. the effect was found to be almost double in FRC when compared to plain concrete. It therefore justifies that the fibres contributed to changes in phases of the composite structure of the FRC.

4.2.6 Output from RVE model for BFRC and Plain concrete

a) Consideration for Loading

Uniaxial Tension and compression pressure loads were defined as tensile and compression loads. The experimental results obtained for the ultimate tensile and compressive strengths plain concrete and Banana fibre reinforced concrete of fibre length 40 mm and fibre content of 0.10 % was 2.35 MPa and 2.50 MPa; and 26.3 MPa and 29.9 MPa respectively.

To model the behaviour of banana fibres and plain concrete, lower strength values for compressive and split tensile strength were selected and applied to the RVE as pressure loads and applied at different loading proportions starting from 25 %, 50 % and 75 % of the ultimate tensile and compressive strengths respectively.

Failure criterion applied

Output from structural FEA are provided in the form of stresses. The appropriate failure criteria was used.

Tension: Maximum Principal stress failure criterion had the highest values and therefore used to assess the mode of failure and it states that failure of a material is predicted to occur when the applied load results in stresses that are equal or exceeds the ultimate tensile strength of the material.

Compression: The von mises failure criterion had the highest values and therefore used to assess the mode of failure of the RVE under compression. The failure criterion states that failure of a material is predicted to occur when the applied load results in stresses that are equal or exceeds the ultimate compressive strength of the material. The results are presented in table 4.2.

Table 4.2:3D RVE Model under compression and tensile loading

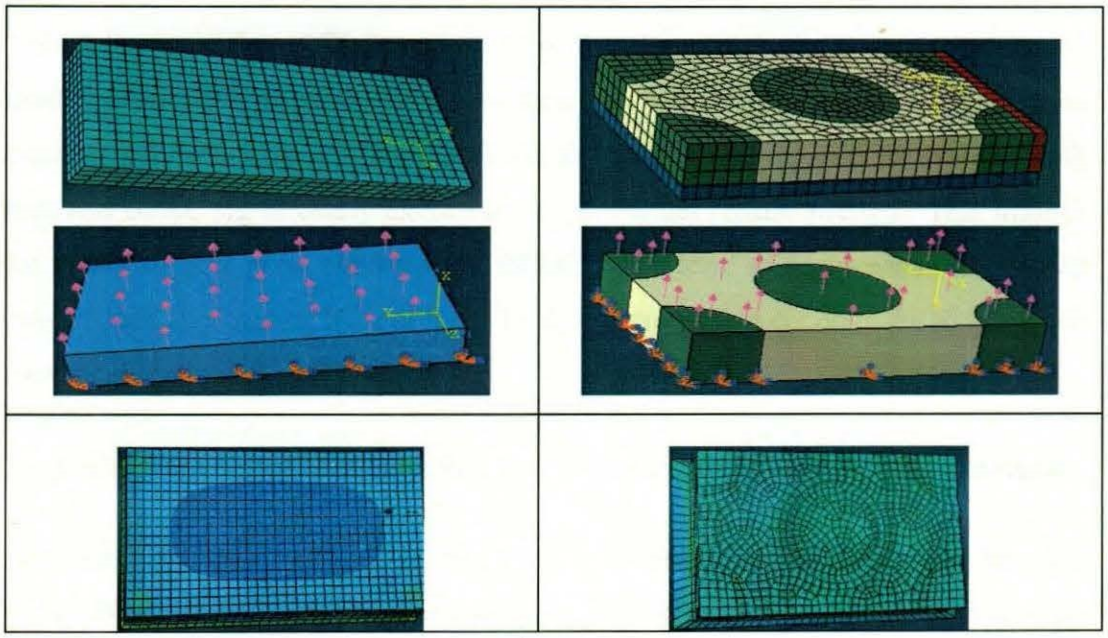


Table 4.3: Model deformation under tension and compression loading

TENSILE LOAD							
Experimental results (UTS)		PC	Fibre content- 0.00%			2.35 MPa	
		BFRC	Fibre content- 2.50%			2.50 MPa	
Experimental results (UTS) considered in the Model						2.35 MPa	
Proportion of the applied load		25%		50%		75%	
Calculated load		0.5875		1.175		1.7625	
Concrete Type		PC	BFRC	PC	BFRC	PC	BFRC
Fibre content			2.50%		2.50%		2.50%
Von Mises		1.133	0.781	2.265	1.562	3.398	3.124
Principal Stresses	$\sigma 11$	1.35	0.799	2.701	1.597	4.015	3.195
Compression Load							
Experimental results (UCS)		PC	Fibre content- 0.00%			26.3 MPa	
		BFRC	Fibre content- 0.10%			29.9 MPa	
Experimental results (UCS) considered in the Model						26.3 MPa	
Proportion of the applied load		25%		50%		75%	
Calculated Pressure load		6.575		13.15		19.73	
Concrete Type		PC	BFRC	PC	BFRC	PC	BFRC
Von Mises		12.676	8.746	25.652	17.492	38.028	34.984
Principal stresses		-6.093	0.220	-12.19	0.439	-18.28	0.878

UTS- Ultimate Tensile Strength ; UCS- Ultimate Compressive strength

b) Comparison between modelled and experimental outputs under Tension

Table 4.3 reveals that at 25 % and 50 % of the ultimate tensile strength (UTS), the simulated principle stresses were less than the respective strength of both plain concrete and BFRC. At 75 % of the UTS, the simulated principle stresses for both plain and BFRC significantly exceed the experimental tensile strength. This implies that failure of both plain concrete and BFRC is predicted to occur when the applied pressure load approaches 50 % of the UTS. Conversely plain concrete failed at a much lower pressure load than BFRC

c) Comparison between modelled and experimental outputs under compression

Table 4.3 reveals that at both 25 % and 50 % of the ultimate compressive strength (UCS), the simulated Von Mises stresses are less than the respective strength of plain concrete and BFRC. At 75 % of the UCS, the simulated Von Mises stresses for BFRC exceed the experimental tensile strength for both plain concrete and BFRC. This implies that failure of both plain concrete and BFRC is predicted to occur when the applied pressure load exceeds 50 % of the UCS. Plain concrete failed at a much lower pressure load than BFRC.

d) Discussion of FEM Results

The results for plain and Banana fibre reinforced concrete tested under tensile and compression loading conditions confirm the role of fibres in bridging and preventing further expansion and propagation of cracks through sharing and redistribution of stresses across the matrix (Mobasher, 2012). The high strength values as seen in plain concrete can be attributed to the presence of high shear stresses which resulted in deformation than BFRC. It implies that the inclusion of Banana fibres in concrete can absorb more energy and resist failure than plain concrete.

CHAPTER- 5 : CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions,

In this study, the effect of Banana fibres on the mechanical and microstructural properties of concrete, has been studied experimentally coupled with an FEM model of the behaviour of Banana fibres in concrete. The independent variables of the study were: (1) Plain concrete (2) Banana fibre reinforced concrete. Fibre content (0.10 %, 0.25 %, 1.00 %, 1.50 %, and 2.50 %) and (3) Fibre length (40, 50 and 60 mm). This chapter presents the findings and conclusions.

1. **Properties of Banana fibres:** Diameter, 102.85 μm, mean breaking force, 142.17 gf, Elongation at break 3.22%, while average tensile strength was 167.89 MPa.
2. Effect of Banana fibres on concrete mechanical properties.
    - **Compressive strength:** There was an increase in the compressive strength of concrete of up to 13 % as the fibre content reduce from 2.5 %, 1.50 %, 1.00 %, 0.25 % to 0.10 %. The fibre length and fibre content that resulted in optimum compressive strength were 40 mm and 0.10 %. The mean strength obtained was 26.62 MPa, standard deviation, 2.71, coefficient of variation was 10.48 % and there was a negative correlation coefficient of 97.1 % for BFRC.
    - **Flexural strength:** Increasing fibre content beyond the optimum fibre content resulted in a reduction in flexural strength of concrete. The maximum increase in flexural strength was 10 %. The fibre length and fibre content that resulted in optimum flexural strength were 40 mm and 2.5 % respectively. The mean strength obtained was 8.92 MPa, standard deviation, 0.869, coefficient of variation was 9.73 % and there was a negative correlation coefficient of 82.6 % for BFRC.
    - **Split tensile strength:** Concrete with fibre inclusion exhibited the ability to absorb energy and resist cyclic loads more than plain concrete. Banana fibre reinforced concrete exhibited the increase in residual split tensile strength at the 4th loading cycle of up to 42 %. Increase in fibre content positively impacted on the split tensile strength of concrete at relatively lower fibre dosages of up to 1 %, but the effect was more pronounced in longer fibres.

3. **Microstructural characterization:** Incorporation of banana fibres in concrete improved its microstructure through better bonding between the fibres and the matrix as well as a reduction in the size of ITZ and consequently the porosity of the matrix by filling its pores which ultimately resulted in improved mechanical properties of the composite. XRD graphs revealed a higher intensity with BFRC (25 counts occurring at an angle (2θ) of 3.04) than plain concrete (13 Counts occurring at an angle (2θ) of 4.28) and directly resulted in improved concrete strength.
4. FEM model predictions that was made in ABAQUS software revealed that incorporation of fibres enhanced the strength of concrete. Plain concrete failed faster as the loading approached 50 % of the applied load than BFRC where failure occurred after application of 50 % of the loading rate under both tension and compression conditions.

5.2 Recommendations- Future Investigations

For optimal purposes, addition of banana fibres should be limited to a maximum of 1% fibre content preferably using shorter fibres. Further studies should however be carried out to establish the following;

1. Seek support from institutions and government sector agencies to extensively explore this potential construction material (Further research, mass production, packaging);
2. Effect of concrete mixing methods on the strength of Banana fibre reinforced concrete
3. To explore on new technologies that can be used for fibre dispersion;
4. Equip university laboratories. For example Computer-controlled Electro-Hydraulic Servo Universal Testing Machine (UTM) (Testometric) integrated with Data Acquisition System to carryout mechanical strength tests;
5. Additional research on the Effect of Banana fibres on Shrinkage Cracking of concrete (Shrinkage Moulds and strain gauges).

References

Abd, M., Akil, M. &. M. & Bakar, H. &., 2007. Chemical Modification of kenaf fibers. *Material Letters,* Volume 61, pp. 2023-2025.

ACI 207.2R-95, 2002. *Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete,* Farmington Hills: American Concrete Institute.

ACI 211.1-91, 2002. *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete,* Farmington Hills: American Concrete Institute.

ACI 224R-01, 2001. *Control of Cracking in Concrete Structures,* Farmington Hills: American Concrete Institute.

ACI 544.1R-96, 2002. *Report on Fiber Reinforced Concrete,* Farmington Hills: American Concrete Institute.

ACI 544.4R-18, 2018. *Guide to Design with Fiber-Reinforced Concrete,* Farmington Hills: American Concrete Institute.

Ahmad, R., Hamid, R. & Osman, S., 2019. Physical and Chemical Modifications of Plant Fibers for Reinforcement in Cementitious Composites. *Advances in Civil Engineering,* Volume 2019, p. 5185806.

ASTM C1116/C1116M-10a, 2015. *Standard Specification for Fiber-Reinforced Concrete,* West Conshohocken: ASTM International.

ASTM C125, 2016. *Standard Terminology Relating to Concrete and Concrete Aggregates,* West Conshohocken: ASTM International.

ASTM C143/C143M-20, 2020. *Standard Test Method for Slump of Hydraulic-Cement Concrete,* West Conshohocken, PA: ASTM International.

ASTM C150/C150M - 20, 2020. *Standard Specification for Portland Cement,* West Conshohocken, PA: ASTM International.

ASTM- C1609/C1609M-19a, 2019. *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading),* West Conshohocken, PA: ASTM International.

ASTM C1723-16, 2016. *Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy,* West Conshohocken, PA: ASTM International.

ASTM C1723-16, 2016. *Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy,* West Conshohocken, PA: ASTM International.

ASTM C293/C293M-16, 2016. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading),* West Conshohocken, PA: ASTM International.

ASTM C31/C31M-19, 2019. *Standard Practice for Making and Curing Concrete Test,* West Conshohocken, PA: ASTM International.

ASTM C33/C33M-18, 2018. *Standard Specification forfor Concrete Aggregates,* West Conshohocken, PA: ASTM International.

ASTM C496/C496M–17, 2017. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,* West Conshohocken, PA: ASTM International.

ASTM- C856-95, 1998. *Standard practice for petrographic examination of hardened concrete,* West Conshohocken, PA: ASTM International.

ASTM D7357, 2019. *Standard Specification Cellulose Fibers for Fiber-Reinforced Concrete,* West Conshohocken: ASTM International.

AtlasBig.com, 2018. *World's Leading Banana Producing Countries.* [Online] Available at: https://www.atlasbig.com/en-au/countries-by-banana-production [Accessed 03 02 2021].

Barbero, E. J., 2008. *Finite Element Analysis of Composite Materials.* London: Taylor and Francis Group.

Bargmann, S. et al., 2018. Generation of 3D representative volume elements for heterogeneous materials: A review. *Progress in Materials Science,* 98(2018), pp. 322-384.

Barros, J. A., Silva, F. d. A. & Filho, R. D. T., 2016. Experimental and numerical research on the potentialities of layered reinforcement configuration of continuous sisal fibers for thin mortar panels. *Construction and Building Materials,* 102(Part 1), pp. 792-801.

Bentur, A. & Mindess, S., 2007. *Fibre Reinforced Cementitious Composites.* 2nd ed. London and New York: Taylor & Francis.

Brandon, D. & Kaplan, W. D., 2008. *Microstructural Characterization of Materials.* 2nd ed. Chichester,West Sussex, England: John Wiley & Sons.

Breuer, K. & Stommel, M., 2019. RVE modelling of short fiber reinforced thermoplastics with discrete fiber orientation and fiber length distribution. *Springer Nature,* 2(19), p. 13.

BS EN 12390-1, 2012. *Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds,* London: British Standards Institution.

BS EN 12390-2, 2019. *Testing hardened concrete. Making and curing specimens for strength tests,* London,: British Standards Institution.

BS EN 12390-3, 2009. *Testing hardened concrete. Compressive strength of test specimens,* London: British Standards Institution.

CEB-FIP Model Code , 2010. *CEB-FIP Model Code for Concrete Structures,* Rotherstraße 21, 10245 Berlin, Germany: Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG,.

Chandramouli, K., Pannirselvam, N., NagaSaiPardhu, D. V. & Anitha, V., 2019. Experimental Investigation on Banana Fibre Reinforced Concrete with Conventional Concrete. *Research gate,* 7(6S).

Chandrasekar, M., Ishak, M. R. & Sapuan, S. M., 2017. A review on the characterisation of natural fibres and their composites after alkali treatment and water absorption. *Plastics, Rubber and Composites,* 46(3), pp. 119-136.

Dhawan, A., Gupta, N., Goyal, R. & Saxena, K. K., 2020. *Evaluation of mechanical properties of concrete manufactured with fly ash, bagasse ash and banana fibre.* s.l., Materials Today.

Elbhiery, A., Elnawawya, O. & Kassemb, M., 2020. Performance of concrete beams reinforced using banana fiber bars. *Case Studies in Construction Materials,* Volume 13, pp. 1-13.

Ellen, K. J., Mondoringin, M. R. & Manalip, H., 2018. Basic Behaviour of Natural Banana Stem Fiber Reinforced Concrete Under Uniaxial And Biaxial Tensile Stress. *International Journal of GEOMATE,* 14(44), pp. 166-175.

Girijappa, T. Y., Rangappa, M. S., Parameswaranpillai, J. & Siengchin, S., 2019. Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review: 10.3389/fmats.2019.00226. *Polymeric and Composite Materials,* 6(226), p. 14.

Gitman, I. M., Askes, H. & Sluys, L. J., 2006. Representative volume: Existence and size determination. *Engineering Fracture Mechanics,* 74(2007), pp. 2518-2534.

Goldstein, J. I., Newbary, D. E. & Michael, J. R., 2018. *Scanning Electron Microscopy and X-Ray Microanalysis.* New York: Springer.

Gram, H.-. E., 1983. *Durability of Natural Fibers in Concrete,* Stockholm: Swedish Cement and Concrete Research Institute.

Hill , R., 1963. Elastic properties of reinforced solids: Some theoretical principles. *Journal of the Mechanics and Physics of Solids,* 11(5), pp. 357-372.

Humphrey, D., 2020. Influence of Plantain Pseudostem Fibres and Lime on the Properties of Cement Mortar. *Advances in Materials Science and Engineering,* 2020(4698603), p. 9.

Kampala Cement limited, 2019. *Chemical composition of OPC CEM I 42.5N,* Kampala: s.n.

Karsli, G. N. & Aytac, A., 2014. Properties of alkali treated short flax fiber reinforced poly(lactic acid)/polycarbonate composites, 10.1007/s12221-014-2607-4. *Fibers Polym,* Volume 15, p. 2607–2612.

Klemm, D., Philipp, B., Heinze, T. & Heinze, U., 1998. *Comprehensive Cellulose Chemistry; Volume 1: Fundamentals and Analytical Methods.* 1st ed. Weinheim: Wiley-VCH.

Koohestani, B., Darban, A. K., Mokhtari, P. & Yilmaz, E., 2019. Comparison of different natural fiber treatments: a literature review. *International Journal of Environmental Science and Technology,* Issue 10.1007/s13762-018-1890-9, pp. 629-642.

Kushwaha, P. & Kumar, R., 2009. Enhanced Mechanical Strength of BFRP Composite Using Modified Bamboos. *Journal of Reinforced Plastics and Composites,* 28(23), pp. 2851-2859.

Li, V. C. & Wu, H. C., 1992. Conditions for pseudo strain-hardening in fiber reinforced brittle matrix composites. *Applied Mechanics,* 45(8), pp. 390-398.

Li, Z., Wang, X. & Wang, L., 2006. Properties of hemp fibre reinforced concrete composites; https://doi.org/10.1016/j.compositesa.2005.01.032. *Part-A Applied Science and Engineering* , 37(3), pp. 497-505.

Mallick, P. K., 2008. *Fiber Reinforced Composites- Materials Manufacturing and Design.* 3rd ed. London: Taylor & Francis Group.

Manalo, A. C., Wani, E., Zukarnain, N. A. & Karunasena, W., 2015. Effects of alkali treatment and elevated temperature on the mechanical properties of bamboo fibre-polyester composites. *Composites Part B: Engineering,* Volume 80, pp. 73-78.

Mehta, K. P. & Monteiro, P. J. M., 2006. *CONCRETE Microstructure, Properties and Materials.* 3 ed. London: McGraw-Hill.

Mindess, P.-C. A. a. S., 2011. *Sustainability of Concrete.* s.l.:Taylor & Francis e-Library.

Mishnaevsky Jr, L., 2007. *Computational Mesomechanics of Composites.* West Sussex, England: John Wiley & Sons Ltd.

Mobasher, B., 2012. *Mechanics of Fiber and Textile Reinforced Cement Composites.* London: CRC Press- Taylor & Francis group.

Mohanty, A. K., Misra, M. & Drzal, L. T., 2005. *Natural Fiber–Rubber Composites and Their Applications.* 1st ed. s.l.:Taylor & Francis.

Mukhopadhyay, S. & Bhattacharjee, B., 2016. Influence of fibre dispersion on compression strength of banana fibres reinforced concrete. *Journal of Industrial Textiles,* 45(5), pp. 957-964.

Mukhopadhyay, S. & Fangueiro, R., 2009. Physical Modification of Natural Fibers and Thermoplastic Films for Composites- A Review. *Journal of Thermoplastic Composite Materials,* 22(2), pp. 135-162.

Musa, P., 2021. *fibres,* kampala: romann.

Nemati, K. M. & Stroeven, P., 2001. Stereological analysis of micromechanical behavior of concrete. *Materials and Structures Constructions,* Volume 34, pp. 486-494.

Neville, A. M., 2011. *Properties of Conrete.* 5 ed. Edinburgh: Pearson Education Limited.

Pickering, K. L., Efendy, A. M. & Le, T. M., 2016. A review of recent developments in natural fibre composites and their mechanical performance. *Composites,* A(83), pp. 98-112.

Polona, D. D., 2010. *Woven Fabric Engineering.* 1st ed. Rijeka, Croatia: Sciyo.

Prasannan, D. et al., 2018. Comparative Study of Banana and Sisal Fibre Reinforced Concrete with Conventional Concrete. *International Journal of Pure and Applied Mathematics,* 118(20), pp. 1757-1765.

Ravi, K., Selin, C. & Dr. Ramasamy, V., 2015. Effect of Fibers In Concrete Composites. *International Journal of Applied Engineering Research,* 10(ISSN 0973-4562), pp. pp. 419-430.

Sahu, P. & Gupta, M. K., 2019. A review on the properties of natural fibres and its bio-composites: Effect of alkali treatment. *SAGE,* 234(1), pp. 198-217.

Savastano Jr., H., Warden, P. G. & Coutts, R. S., 2000. Brazilian waste fibrers as reinforcement for cement-based composites. *Cement and Concrete composites,* 22(5), pp. 379-384.

Savastano Jr, H., Warden, P. G. & Coutts, R. S. P., 2005. Microstructure and mechanical properties of waste fibre–cement composites. *Cement & Concrete Composites,* Volume 27, pp. 583-592.

Sciegaj, A. et al., 2020. Upscaling of three-dimensional reinforced concrete representative volume elements to effective beam and plate models. *International Journal of Solids and Structures,* 202(2020), pp. 835-853.

Sinohydro, 2019. *Grading results for coarse aggregates used at Karuma Hydropower project,* Kampala: Sinohydro Corporation limited.

Sinohydro, 2019. *Physical properties of coarse and fine aggregates,* Kampala: s.n.

Sinohydro, 2019. *Physical Tests- Results of Cement used at Karuma Hydropower project,* Kampala: Sinohydro Corporation limited.

Sinohydro, 2019. *Sieve analysis results of fine aggregates,* Kampala: Sinohydro Corporation limited.

Sivaraja, M., Kandasamy, Velmani, N. & Sudhakaran, M. P., 2010. Study on durability of natural fibre concrete composites using mechanical strength and microstructural properties. *Bulletin of Materials Science,* 33(6), pp. 719-729.

Susheel, K., Kaith, B. S. & Inderjeet, K., 2009. *Review on Pre-treatments of Natural Fibers and their Application as Reinforcing Material in Polymer Composites,* s.l.: Wiley InterScience.

Tehmina, . A., Nasir, S. & Nuruddin, M. . F., 2014. Effect of Chopped Basalt Fibers on the Mechanical Properties and Microstructure of High Performance Fiber Reinforced Concrete. *Advances in Materials Science and Engineering,* 2014(587686), p. 14.

Venkateshwaran, N., Perumal, A. & Arunsundaranaya, D., 2013. Fiber surface treatment and its effect on mechanical and visco-elastic behaviour of banana/epoxy composite. *Materials and Design,* Volume 47, pp. 151-159.

Wallenberger, F. T. & Norman, W. E., 2004. *Natural Fibers, Plastics And Composites.* 2nd ed. New York: Springer Science and Business media, LLC.

Wang, W., Dai, Y., Zhang, C. & Gao, X., 2016. Micromechanical Modeling of Fiber-Reinforced Composites with Statistically Equivalent Random Fiber Distribution. *Materials,* 9(624), p. 14.

Xiong, X., Shen, S. Z., Hua, L. & Liu, J. Z., 2018. Finite element models of natural fibers and their composites: A review. *Reinforced Plastics and,* 37(9), pp. 617-635.

Yan, B. L., Chouw, N. & Yuan, W. X., 2012. Improving the mechanical properties of natural fibre fabric reinforced epoxy composites by alkali treatment. *Journal of Reinforced Plastics and Composites,* 31(6), pp. 425-437.

Zhang, P., Song, H., Serina, N. & Xu, H., 2018. Fiber-Reinforced Concrete with Application in Civil Eng. *Hindawi,* 2018(1698905), p. 4.

Zollo, R. F., 1997. Fiber-reinforced Concrete, An Overview after 30 Years of Deveopment. *Elsevier Science ltd,* 19(2), pp. 107-122.

Zongjin, L., 2011. *Advanced Concrete Technology.* Hoboken, New Jersey: Wiley.

APPENDICES

A- Mix design calculations

Design- DATA

♦ Design compressive strength at 28 days	C20/25 MPa
♦ Type of cement	CEM-I 42.5N (OPC)
♦ Manufacture	Kampala cement company ltd
♦ Cement density	$1400 \mathrm{kg/m^3}$
♦ Specific gravity of cement, G_c	3.15
♦ Type of Aggregates	Crushed- Granite Gneiss
♦ Aggregate density	$2700 \mathrm{kg/m^3}$
♦ Moisture content of aggregate	SSD
♦ Nominal Maximum Size Aggregate (NMSA)	19 mm
♦ Maximum Water-Cement ratio	0.45
♦ Workability/Slump	25-50 mm
♦ Bulk Specific gravity of Coarse aggregates	2.85
♦ Bulk specific gravity of Fine aggregates	2.80
♦ Fineness Modulus (FM)	2.86

STEPS FOLLOWED TO DEVELOP THE MIC PROPORTIONS

Desired Concrete Properties	
Parameter	**Result**
Step –I	
♦ Choice of Nominal Maximum Size of Aggregate (mm)	19
♦ Selection of Concrete Slump (mm) (Table 6.3.1)	25-50
♦ Maximum W/C Ratio; From Table 6.3.4(a) and (b),	0.45
♦ Estimated maximum placement temperature	23 °C
♦ Based on the available historical data at the Karuma project site; standard deviation of 4.0 MPa and 1.65 assuming 5 % defective was adopted. The Mean target strength was computed as follows: ♦ $f^{I}_{ck} = f_{ck} + 1.655 * \sigma = (25 + 1.65x4.0) = 32$ MPa ♦ The concrete was designed under moderate exposure conditions also corresponding to XC2, (BSI, 1992). ♦ Tests on aggregate are given in the Tables 3.7 ~ 3.8 ♦ Type of Cement: CEM-I- 42.5 N, OPC	
Step-2	
♦ Properties of cement, aggregates (coarse and fine) and water are given in Table 3.5 ~ 3.9. The Tables give the sieve analysis results, bulk specific gravities, absorptions. fineness modulus, specific gravity of cement including physical and chemical properties	
Step-3 Selection of W/C ratio	
♦ Table A5.8, provide the maximum permissible W/C ratio by weight for massive sections corresponding to the exposure conditions. To obtain the	0.45

desired average strength of 32 MPa; the designed W/C ratio was taken as 0.45, for Concrete deposited in water.	
Step 4- Estimation of mixing water, kg/m^3	
◆ Table 6.3.3, was used to determine the approximate mixing water and air content requirements based on concrete slump of (25~50 mm) and the selected 19 mm NMSA- crushed well-shaped angular aggregates and was determined to be 200 kg/m^3	200
Step 5: Selection of air content	
◆ According to the standard, air content seems to apply in aggregates ranging from 37.5 mm and above. The nominal maximum size of aggregates considered for this research was 19 mm; based on that, air content was not considered	/
Step 6: Weight of cement from selected W/C ratio and water demand	
◆ From Step 3, W/C = 0.45. Therefore: weight of cement in a total cement mixture equals $\left(C_w = \frac{200}{0.45} = 444\ kg/m^3\right)$	**444**
Step 7 - Absolute volume per cubic meter (m^3)	
◆ This was calculated using the equation from ACI 211 as follows;	
◆ **Volume of Cement:**	
◆ $V_c = \left\{\left(\frac{Mass\ of\ Cement,\ C_w}{Specific\ gravity\ of cement, G_c}\right) \times \frac{1}{1000}\right\} = \frac{444}{3.15\times1000} = 0.141\ m^3/m^3$	**0.141**
◆ **Volume of Water**	
◆ $V_w = \left\{\left(\frac{Mass\ of\ Water,\ M_w}{Specific\ gravity\ of\ Water}\right) \times \frac{1}{1000}\right\} = \frac{200}{1\times1000} = 0.20\ m^3/m^3$	**0.200**
Step 8: Percentage of Coarse aggregates	

◆ The FM of crushed fine aggregates was 2.86 while the Nominal maximum aggregate size was 19 mm, therefore, the volume of coarse aggregate used was obtained using Table A5.5 as 62 %		0.62
Step 9 - Absolute volume of fine and coarse aggregates		
◆ Total volume of aggregate ◆ $1.0 - V_w - V_C = 1.0 - 0.200 - 0.141 = 0.659\ m^3/m^3$		**0.659**
◆ Volume of coarse aggregates: $0.659 \times 0.62 = 0.409\ m^3/m^3$		**0.409**
◆ Volume of fine aggregates: $0.659 \times 0.38 = 0.250\ m^3/m^3$		**0.250**
Step 10 – Aggregate combinations		
◆ The range of aggregates was; 4.75 to 19 mm		
Step 11 - Convert all absolute volumes to weight per unit volume (kg/m^3). (absolute volume × specific gravity × 1000)		
◆ Portland Cement:	◆ $0.141 \times 3.15 \times 1000 = 444$	**444**
◆ Water	◆ $0.200 \times 1.00 \times 1000 = 200$	**200**
◆ Fine aggregates	◆ $0.250 \times 2.80 \times 1000 = 700$	**700**
◆ Coarse aggregates	◆ $0.409 \times 2.85 \times 1000 = 1165$	**1165**
Step 11- Check Mortar content		
$Mortar\ content = V_c + V_w + V_{FA} + V_{CA}$ $\mathbf{0.141 + 0.200 + 0.250 + 0.409 = 1.0 - \mathit{O.K}}$		
◆ Weight of fresh concrete (Table 6.3.7.1) (kg/m^3)		**2348.28**
Adjustment for Moisture content & Absorption		

Tests indicate total moisture of 0.086 % and absorption of 0.37 % in the coarse aggregates; and 1.29 % and 0.61 % in the fine aggregate. **Adjusted aggregate masses:** Coarse aggregate (wet) $=1165 \times 1.055= 1166$ Fine aggregates (wet) $= 700 \times 1.0129 = 709$ kg Absorbed water does not become part of the mixing water and must be excluded from the adjustment in added water. Thus, surface water contributed by the aggregate were calculated as follows: Coarse aggregate (wet) $=0.37- 0.086 = 0.284$ Fine aggregates (wet) $= 1.29- 0.62= 0.67$ $=200 - (\frac{0.284}{100}) \times 1166 - (\frac{0.67}{100}) \times 709 = 192$	**192**

B- Test Results

Appendix Table B.1: Results obtained from electronic single fibre strength tester

No. of Cycles	Sample No.								
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
C1	147.21	147.2	148.7	148.49	145.23	145.58	149.03	148.66	145.67
C2	148.91	143.57	147.72	146.41	146.28	146.21	149.54	143.58	147.29
C3	148.66	146.41	146.36	146.82	144.92	146.1	149.67	144.61	149.84
Average force (gf)	148.26	145.73	147.59	147.24	145.48	145.96	106.08	145.62	147.6
	Average Elongation (%)								
	3.23	3.1	3.33	3.9	2.8	2.85	2.85	3.9	3.05
	Average Tensile strength (MPa)								
	175.08	172.088	174.292	173.875	171.792	172.367	125.269	171.958	174.3

Appendix Table B.2: Compressive strength Test results

Age of concrete	14 days			28 days		
	Fibre length			Fibre length		
Fibre Content	40	50	60	40	50	60
0.10%	27.3	22.6	26.8	29.9	27.5	29.6
0.25%	26.2	22	25.5	28.4	27.2	28
1.00%	24.4	21.8	22.4	27.2	26	23.7
1.50%	21.7	21	19.8	24.5	23.7	22.3
2.50%	20.8	20.5	19.7	23.1	22.4	20.6
3.00% (n-values)	**18.8**	**20.0**	**16.9**	**21.3**	**20.3**	**17.7**
Minimum	20.8	20.5	19.7	23.1	22.4	20.6
Maximum	27.3	22.6	26.8	29.9	27.5	29.6
Mean strength	24.08	21.58	22.84	26.62	25.36	24.84
Standard deviation	2.801	0.832	3.242	2.791	2.230	3.820
Coefficient of Variation	11.63%	3.85%	14.20%	10.48%	8.79%	15.38%
Correlation coefficient	-96.4%	-96.3%	-92.7%	-97.1%	-98.0%	-95.3%
0.00%	24.5			26.3		

Appendix Table B.3: Flexural strength Test results

Flexural Strength						
Age	14 day			28 day		
Fibre Content	Fibre length			Fibre length		
	40	50	60	40	50	60
0.10%	8.4	8	7.35	9.225	8.65	8.025
0.25%	8	7.9	7.2	10.2	8.775	7.8
1.00%	7.95	7.8	6.42	8.45	9.2	7.5
1.50%	7.5	7.35	6.3	8.85	8	7.35
2.50%	7.54	7.425	6.2	7.89	7.15	7.25
3.00% (n-values)	**7.2**	**7.2**	**5.7**	**7.5**	**7.1**	**7.0**
Minimum	7.5	7.35	6.2	7.89	7.15	7.25
Maximum	8.4	8	7.35	10.2	9.2	8.025
Mean strength	7.88	7.70	6.69	8.92	8.36	7.59
Standard deviation	0.371	0.291	0.539	0.869	0.799	0.322
Coefficient of Variation	4.71%	3.78%	8.05%	9.73%	9.57%	4.24%
Correlation coefficient	-86.5%	-88.2%	-90.3%	-82.6%	-81.8%	-93.2%
0.00 %	8.25			9.26		

Appendix Table B.4: Split Tensile strength Test results at 14 days

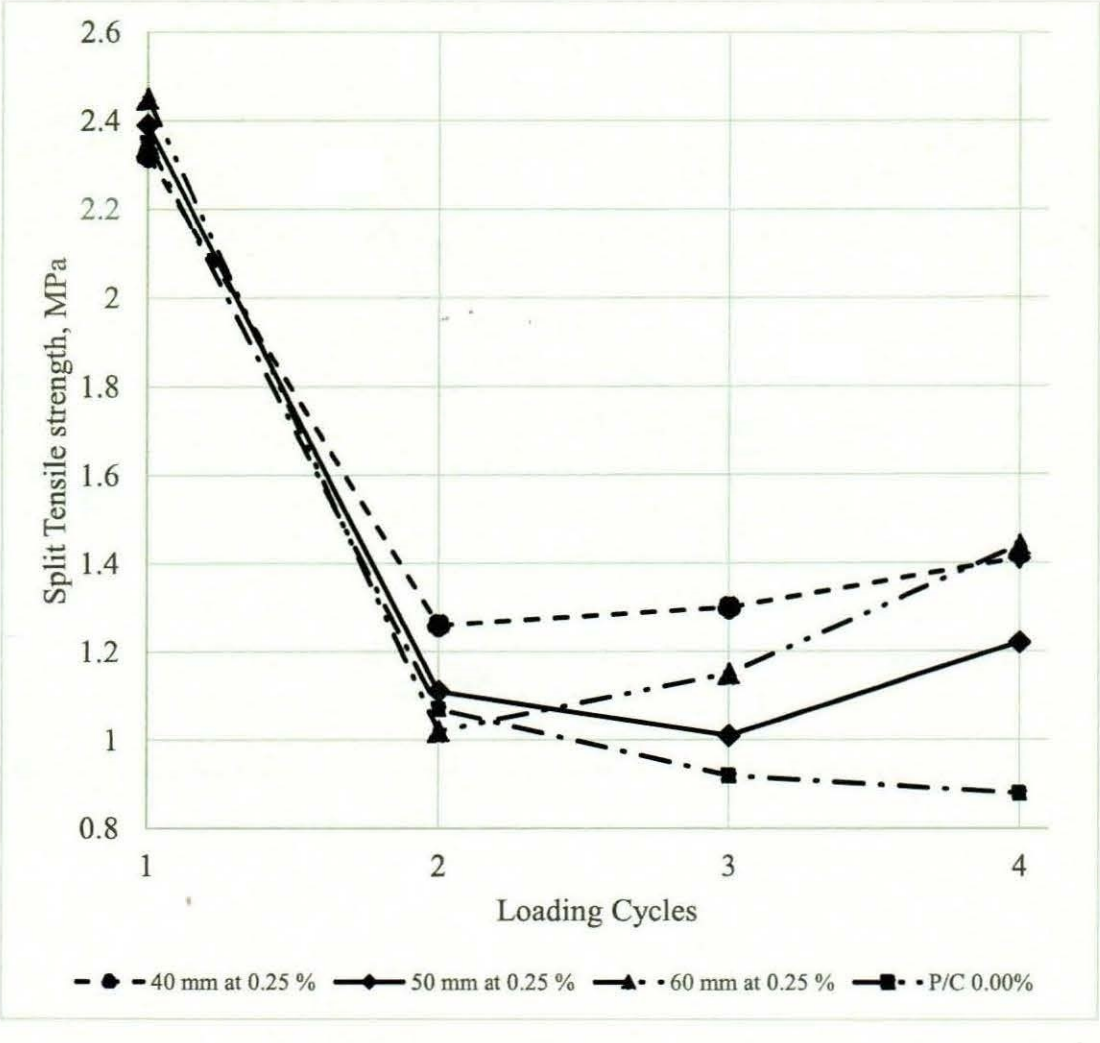
Fibre Content	14 day		
	Fibre length		
	40	50	60
0.10%	2.1	2.18	2.12
0.25%	2.18	2.25	2.2
1.00%	2.15	2.35	2.3
1.50%	2.02	2.1	1.87
2.50%	1.92	1.98	1.8
Minimum	1.92	1.98	1.8
Maximum	2.18	2.35	2.3
Mean strength	2.07	2.17	2.06
Standard deviation	0.105	0.141	0.215
Coefficient of variation	5.08%	6.51%	10.44%
Correlation Coefficient	-87.4%	-70.3%	-76.4%
0.00 %	2.14		

Appendix Table B.5: Split tensile strength at 28 days under Cyclic loading

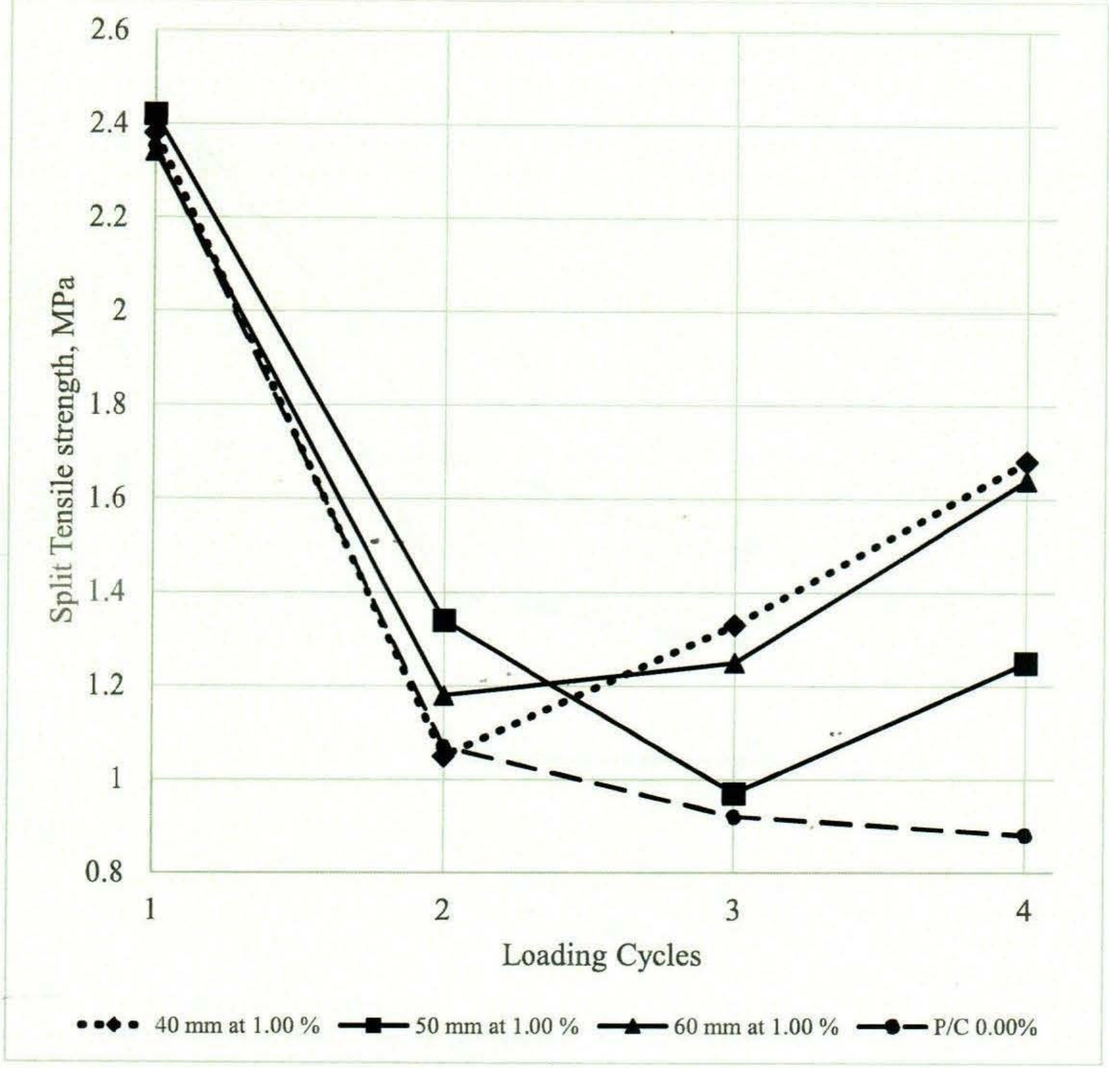
Fibre length (mm)	**Fibre content**	**Loading cycles and the corresponding strengths at 28 days**			
		1st Cycle	2nd Cycle	3rd Cycle	4th Cycle
40	0.10%	2.18	1.31	1.02	1.41
	0.25%	2.32	1.26	1.3	1.41
	1.00%	2.38	1.05	1.33	1.68
	1.50%	2.30	1.61	1.42	1.76
	2.50%	2.50	1.53	1.25	1.41
50	0.10%	2.35	1.29	1.17	1.43
	0.25%	2.39	1.11	1.01	1.22
	1.00%	2.42	1.34	0.97	1.25
	1.50%	2.27	1.35	1.25	1.77
	2.50%	2.15	1.07	1.16	1.5
60	0.10%	2.42	1.05	0.98	1.39
	0.25%	2.45	1.02	1.15	1.44

	1.00%	2.34	1.18	1.25	1.64
	1.50%	2.16	1.03	1.03	1.59
	2.50%	2.03	1.04	0.9	1.44
PC	0.00%	2.35	1.07	0.92	0.88

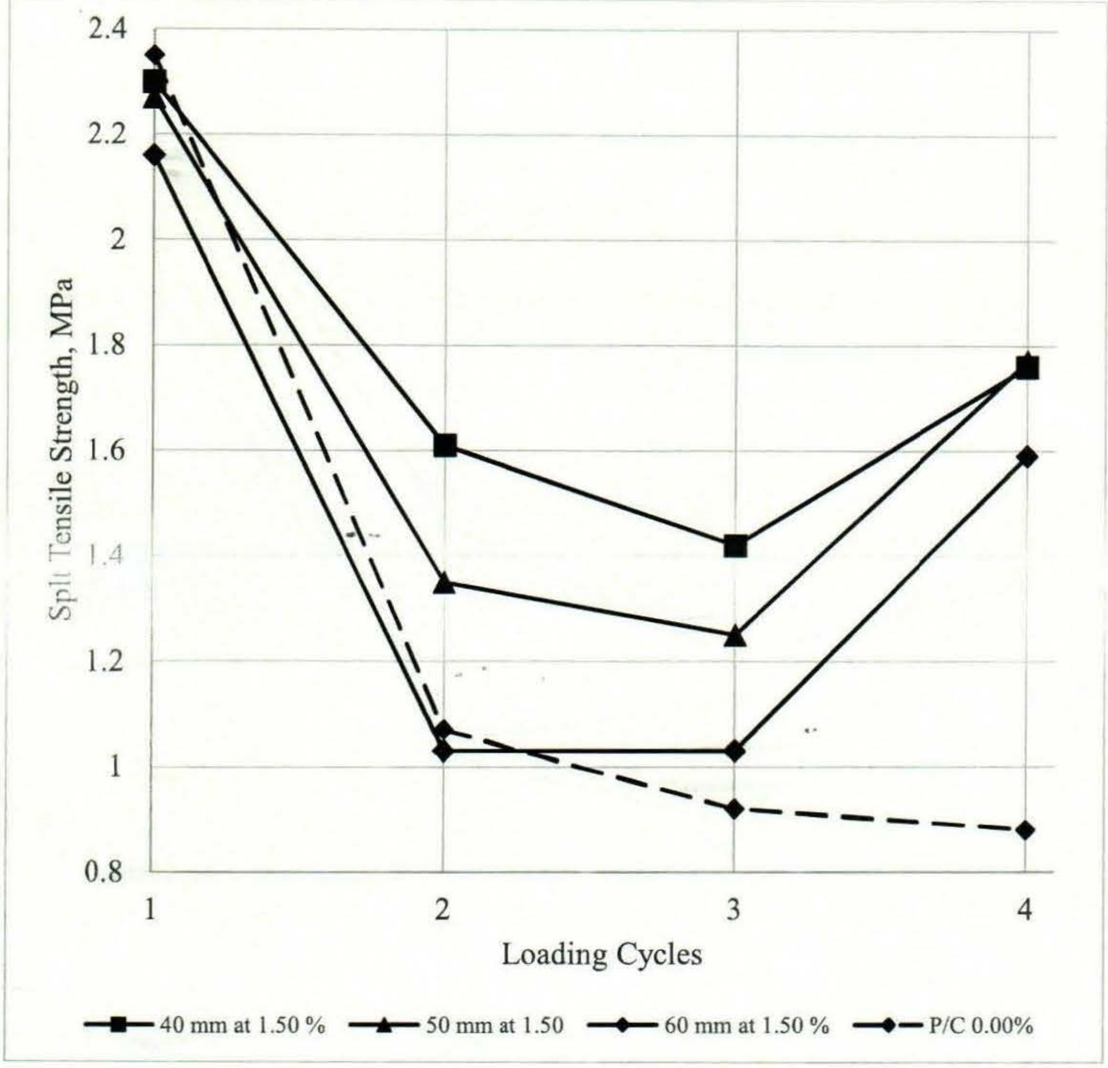
Appendix Figure

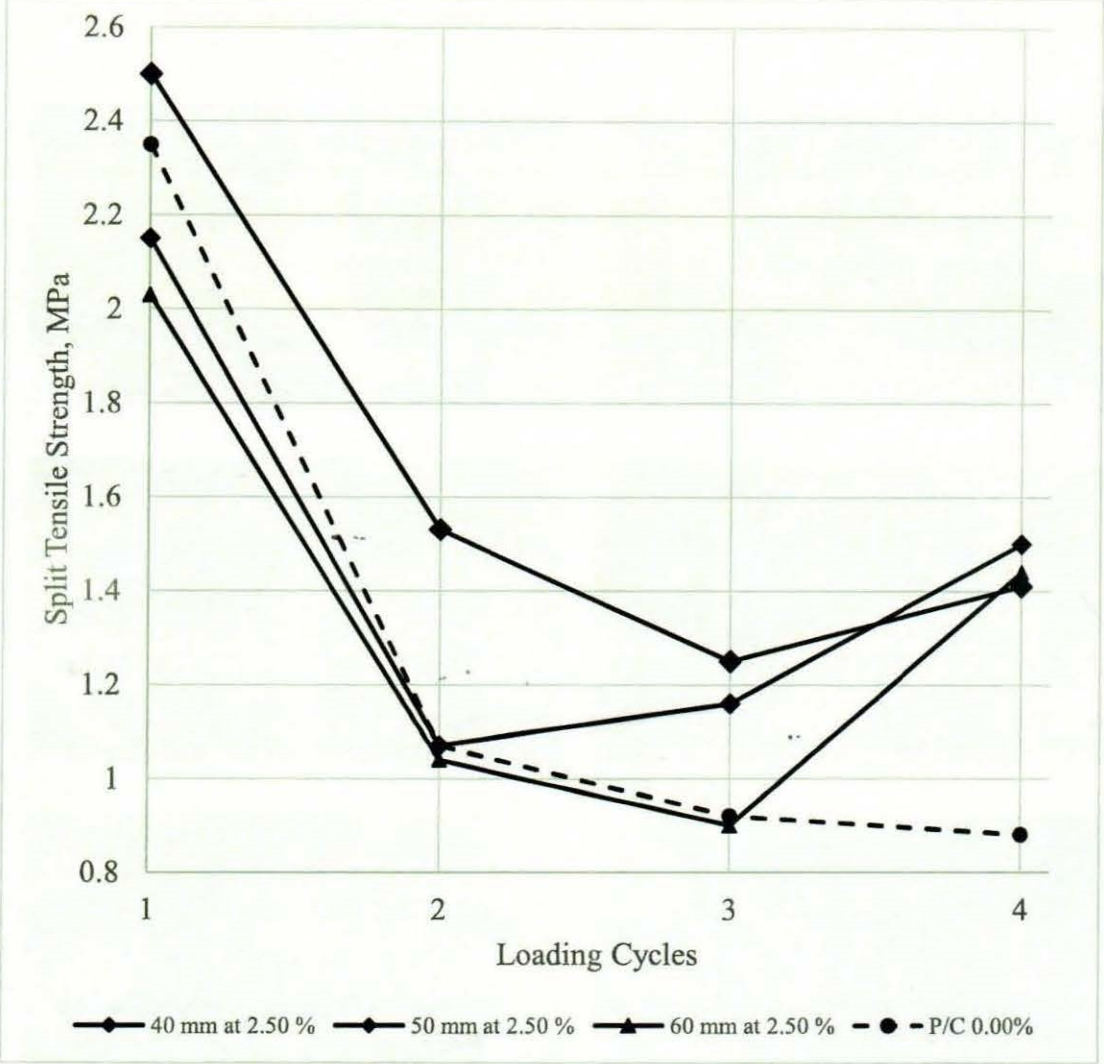


Appendix C1: Residual Strength of Concrete at varying loading cycles at 0.25 % Fibre content



Appendix C2: Residual Strength of Concrete at varying loading cycles at 1.00 % Fibre content


2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
Split Tensile Strength, MPa
1
2
3
4
Loading Cycles
40 mm at 1.50 %
50 mm at 1.50
60 mm at 1.50 %
P/C 0.00%



Appendix C3: Residual Strength of Concrete at varying loading cycles at 2.50 % Fibre content

Table 4.4: Concrete Sample preparation process