

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

A STUDY OF FLEXURAL AND COMPRESSIVE STRENGTHS
OF
JUTE FIBRE-REINFORCED CONCRETE

ENYEW BANTIE

MARCH, 2010

A STUDY OF FLEXURAL AND COMPRESSIVE STRENGTHS
OF
JUTE FIBRE-REINFORCED CONCRETE

A Thesis
Presented to the School of Graduate Studies
Addis Ababa University

In Partial Fulfillment of the Requirements for the Degree Masters of Science in
Civil Engineering (Structures)

by

Enyew Bantie

MARCH, 2010

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
FACULTY OF TECHNOLOGY

A STUDY OF FLEXURAL AND COMPRESSIVE STRENGTHS
OF
JUTE FIBRE-REINFORCED CONCRETE

by
Enyew Bantie

Approved by Board of Examiners:

| <i>Name</i> | <i>Signature</i> | <i>Date</i> |
|-----------------------|------------------|-------------|
| Advisor | | |
| Dr. Asnake Adamu | _____ | _____ |
| Examiner | | |
| Dr. Esayas G/Yohannes | _____ | _____ |
| Examiner | | |
| Dr. -Ing Adil Zekaria | _____ | _____ |

ACKNOWLEDGMENTS

This thesis is done under the supervision of my advisor Dr. Asnake Adamu at Addis Ababa University, Faculty of Technology, Civil Engineering Department. Hence, I am very grateful to his invaluable and indispensable suggestions and thorough follow up in the accomplishment of the thesis work.

I am also grateful to members of the examining board for their academic assessment and comments so as to have a final and standard framework of the thesis.

I would like to extend my deep gratitude to my father Ato Bantie Tamiru, my mother W/ro Fentanesh Ayenew, my brothers and sisters for their honorable and courteous supports all the way through my postgraduate career.

I am indebted to Ato Daniel Kifle for his technical assistant in the accomplishment of the laboratory activities. Finally, I greatly acknowledge the School of Graduate Studies, Addis Ababa University for funding the thesis work.

TABLE OF CONTENTS

| Contents | Page |
|--|-------------|
| ACKNOWLEDGMENTS | III |
| LIST OF TABLES | VII |
| LIST OF FIGURES | IX |
| SYMBOLS AND ABBREVIATIONS..... | X |
| ABSTRACT..... | XII |
| 1 INTRODUCTION | 1 |
| 1.1 Background of the Study..... | 1 |
| 1.2 Objectives and Scope of the Study | 2 |
| 1.3 Contents of the Thesis | 3 |
| 2 A BRIEF REVIEW OF FIBRE-REINFORCED CONCRETE..... | 5 |
| 2.1 Historical Background of Fibre-Reinforced Concrete | 5 |
| 2.2 Material Compositions for FRC | 5 |
| 2.2.1 Cement..... | 6 |
| 2.2.2 Aggregates | 7 |
| 2.2.3 Water | 8 |
| 2.2.4 Fibres | 9 |
| 2.2.5 Admixtures..... | 12 |
| 2.3 Mix Design of the FRC | 13 |
| 2.4 Properties and Test Methods of FRC..... | 15 |
| 2.4.1 General..... | 15 |
| 2.4.2 Properties of FRC..... | 15 |
| 2.4.3 Test Methods for FRC..... | 17 |
| 3 EXPERIMENTAL STUDY OF JFRC..... | 21 |
| 3.1 Experimental Set Up | 21 |
| 3.2 Material Specifications..... | 24 |
| 3.2.1 Water | 24 |

| | | |
|----------|---|-----------|
| 3.2.2 | Cement..... | 24 |
| 3.2.3 | Aggregates | 24 |
| 3.2.4 | Fibre..... | 25 |
| 3.3 | Mix Proportioning and Specimen Preparations | 27 |
| 3.3.1 | Mix Proportioning | 27 |
| 3.3.2 | Mix and Test Specimen Preparations | 30 |
| 3.4 | Experimental Tests..... | 32 |
| 3.4.1 | Compression Test..... | 32 |
| 3.4.2 | Bending Test | 32 |
| 4 | DISCUSSIONS AND ANALYSES ON TEST RESULTS..... | 34 |
| 4.1 | Effects of Jute Fibre on Properties of Fresh Concrete | 34 |
| 4.2 | Effects of Jute Fibre on Mechanical Properties of Concrete..... | 35 |
| 4.2.1 | Compressive Strength..... | 35 |
| 4.2.2 | Flexural Strength..... | 38 |
| 4.2.3 | Toughness Behavior | 45 |
| 4.3 | Design Considerations and Areas of Applications | 46 |
| 5 | CONCLUSIONS AND RECOMMENDATIONS..... | 54 |
| 5.1 | CONCLUSIONS..... | 54 |
| 5.2 | RECOMMENDATIONS | 55 |
| | APPENDIX | 57 |
| | ANNEX | 76 |
| | REFERENCES | 87 |

LIST OF TABLES

| Tables | Page |
|--|-------------|
| <i>Table 2.1</i> Names and Abbreviations of Major Compounds..... | 6 |
| <i>Table 2.2</i> Chemical Composition of Common Vegetable Fibres | 10 |
| <i>Table 2.3</i> Mechanical Properties of Vegetable Fibres..... | 11 |
| <i>Table 3.1</i> Specific Gravity, Absorption Capacity and Unit Weight of Aggregates | 25 |
| <i>Table 3.2</i> Tensile Strength and Extensibility of Jute Fibre..... | 26 |
| <i>Table 3.3</i> Mix Quantities per Cubic Meter of Concrete for Different Fibre Contents ... | 30 |
| <i>Table 3.4</i> Test Programme | 31 |
| <i>Table 4.1</i> Properties of Fresh JFRC..... | 35 |
| <i>Table 4.2</i> Average Compressive Strength of JFRC at 28-Days..... | 36 |
| <i>Table 4.3</i> Average Failure Load and Modulus of Rupture of JFRC at 28-Days..... | 38 |
| <i>Table 4.4</i> Average First-Crack Deflection of JFRC | 43 |
| <i>Table 4.5</i> Comparison of Flexural Strength of Experimental Results with that of Prediction Equation | 44 |
| <i>Table 4.6</i> Toughness Indices and Residual Strength Factors of JFRC..... | 46 |
| <i>Table A-1</i> Procedure and Check List for Sieve Analysis of Aggregates..... | 58 |
| <i>Table A-2</i> Procedure and Check List for the Specific Gravity and Absorption Capacity of Aggregates | 61 |
| <i>Table A-3</i> Procedure and Check List for the Determination of Unit Weight of Aggregates | 64 |
| <i>Table A-4</i> Procedure and Check List for Mix Preparation of JFRC..... | 66 |
| <i>Table A-5</i> Procedure and Check List for the Evaluation of Properties of Fresh JFRC .. | 68 |
| <i>Table A-6</i> Procedure and Check List for Test Specimen Preparation | 70 |

| | | |
|------------------|---|----|
| <i>Table B-1</i> | Unit Weight of Fresh Concrete | 74 |
| <i>Table B-2</i> | Compression Test Results at 28-Days | 74 |
| <i>Table B-3</i> | Bending Test Results at 28-Days | 75 |

LIST OF FIGURES

| Figures | Page |
|--|-------------|
| <i>Figure 3.1.</i> Compression Test Set Up | 22 |
| <i>Figure 3.2.</i> Bending Test Set Up..... | 23 |
| <i>Figure 3.3.</i> Material Preparation | 25 |
| <i>Figure 4.1.</i> Properties of Fresh Concrete..... | 34 |
| <i>Figure 4.2.</i> Compression Test Failures for Different Jute Fibre Content..... | 37 |
| <i>Figure 4.3.</i> Typical Stress-Strain Diagrams for Coir FRC | 38 |
| <i>Figure 4.4.</i> Statical Systems and Bending Moment Diagram..... | 39 |
| <i>Figure 4.5.</i> Bending Test Failures | 40 |
| <i>Figure 4.6.</i> Typical Flexural Load-Deflection Curves for JFRC..... | 41 |
| <i>Figure 4.7.</i> Typical Load-Deflection Curves for FRC | 42 |
| <i>Figure 4.8.</i> Trend Curve of Flexural Strength against Fibre Parameters of JFRC | 44 |
| <i>Figure 4.9.</i> Stress Analysis of FRC in Bending without Additional Steel Reinforcement .. | 47 |
| <i>Figure 4.10.</i> Stress Analysis of FRC in Bending with Additional Steel reinforcement...50 | |
| <i>Figure B.1.</i> Grading Chart of Sand | 72 |
| <i>Figure B.2.</i> Grading Chart of Gravel..... | 73 |

SYMBOLS AND ABBREVIATIONS

| | |
|-----------|--|
| a | Depth of effective tension zone |
| b | Width of beam section |
| C | Resultant compressive force on the compression zone |
| c | Clear cover to reinforcement |
| c_b | Distance of the extreme tensile fibre from neutral axis |
| d | Effective depth of beam section |
| E_{co} | Modulus of elasticity of FRC composite |
| E_f | Modulus of elasticity of fibre |
| E_m | Modulus of elasticity of the concrete matrix |
| f_{cco} | Extreme fibre compressive stress of FRC composite |
| f_{ck} | Characteristic compressive strength |
| f_{ckm} | Characteristic compressive strength of the matrix in FRC |
| f_{ctk} | Characteristic tensile strength |
| f_{rco} | Modulus of rupture of the FRC composite |
| f_{rm} | Modulus of rupture of the matrix |
| f_{tco} | Extreme fibre tensile stress of FRC composite |
| h | Depth of beam section |
| I_g | Gross moment of area of the beam section |
| L | Span of the beam |
| T | Resultant tensile force on the tension zone |
| T_s | Resultant tensile force on the steel reinforcement |
| V_f | Volume percentage of fibre |
| V_m | Volume percentage of concrete matrix |
| X | Neutral axis depth measured from the extreme compression fibre |
| X_c | Distance of the resultant compression force from the extreme compression fibre |

| | |
|---------------------|---|
| Z | Section modulus |
| δ_{cr} | First-crack deflection at mid-span of the beam |
| ε_{cco} | Extreme fibre compressive strain of FRC composite |
| ε_{tco} | Extreme fibre tensile strain of FRC composite |
| JFRC | Jute Fibre-Reinforced Concrete |
| FRC | Fibre-Reinforced Concrete |
| tex | Unit of linear density of fibre, 1tex = 1g/km |

ABSTRACT

The problems associated with low efficiency in tensile strength of structural elements, brittle mode of failure, rapid crack propagation and increased overload are common in the concrete construction industry. Whereas ordinary steel reinforced concrete is the most popular mechanism developed so far to alleviate such problems, it is rather becoming expensive in production costs, transportation of pre-cast members, maintenance costs and the supply of much amount of steel. These impediments have driven the development of contemporary concrete technologies such as high strength concrete and fibre reinforced concrete in which all the advancements entail an investigation into the constitutive materials. This thesis is part of such works dealing with the experimental assessment of flexural and compressive strengths of JFRC with different jute fibre contents. To achieve this objective a series of compression and two point bending tests were conducted.

The results of the compression test indicated that the presence of jute fibre tends to reduce the compressive strength of concrete at higher fibre content. Despite the minimal reduction in the compressive strength at higher jute fibre content, there is an improvement of ductility after cracking of concrete. Similarly, the bending test results indicated that the modulus of rupture of concrete increases by 50% at 0.50% jute fibre content. Moreover, jute fibre significantly improves the toughness behavior of concrete. There is as much as 28%, 82% and 105% increment in I_5 , I_{10} , and I_{20} respectively at 1.00% jute fibre.

In spite of the limited scope of the thesis work and the shortcomings associated with jute fibre, the thesis work results elite a hope that JFRC can be used in areas where small tensile reinforcement is expected and also in the construction of temporary structures. The least cost of jute fibre, its being renewable resources, the reduced weight of the JFRC composite and the reduction in consumption of other constitutes of the concrete matrix would indicate its economic advantage. While an assessment of flexural and compression strengths of JFRC have been shown and described in detail in this thesis, various additional changes and modifications may be made to study other properties of JFRC.

1 INTRODUCTION

1.1 Background of the Study

The classical materials for the largest part of the constructions include brick, concrete, steel, wood and others. Nevertheless, only some of these materials have been evolved into the contemporary technologists because of their competence in the construction environment. Concrete is one of such classical construction materials, which achieved its reputation since the early 1960`s [8]. The application of concrete in the field of structural engineering often involves a technique of reinforcing with other materials, such as steel, so as to complement the undesirable properties.

However, ordinary steel-reinforced concrete construction more than ever is becoming expensive in production costs, transportation of pre-cast members, maintenance costs and the supply of much amount of steel, which takes huge capital investment to produce locally. Moreover, difficulties attributed to low efficiency in tensile strength of structural elements, brittle mode of failure, rapid crack propagation and increased overload are common in the concrete construction industry. These impediments have driven the development of contemporary concrete technologies: high strength concrete, fibre reinforced concrete etc, in which all the advancements entail an investigation into the constitutive materials.

Many investigations [9, 11, 12, 16, 17] have been carried out in the use of various types of fibres to reinforce concrete thereby enhancing the mechanical properties of the same. It has been revealed that concrete reinforced with a permissible amount of fibre acquires better performance in compression, flexure, shear, toughness, energy absorption and micro-mechanical properties, in which case the degree of improvement relies on the types of fibres.

The development of FRC has brought about many changes in cement and concrete technologies and resulted in wide spectra of applications in the construction industries. Structural members made up of FRC have of great significance owing to enhanced physical and mechanical properties apart from its ease of transportation and construction

attributed to light in weight of the FRC technologies. Concrete pathologies formed in such a manner have been utilized in the construction of airfield pavements, manhole covers, industrial floors, nuclear power industries, spillways, repair of concrete constructions, shotcrete, impact loading situations, blast loading situations, deep beams, piles and marine environment [8].

It is worthwhile to mention that FRC has got some short comings. The presence of fibers could impart negative outcomes on the rheological characteristics of the fresh concrete, particularly at high fibre concentrations [7]. The problem of durability due to deterioration of fibres is also one of the issues that would offset the generality of applications, especially in natural fibre-reinforced concrete [17, 18, 20].

Many undertakings are in continuous path in the exploration of FRC technologies. This thesis is part of such works dealing with the experimental assessment of flexural and compressive strengths of Jute Fibre-Reinforced Concrete (JFRC). The study was designed to investigate the rheological characteristics and mechanical properties of JFRC with different jute fiber contents. The compressive strength of the JFRC has been investigated by conducting compression test and that of the flexural strength by bending test. Finally, conclusions and recommendations have been drawn based on the test results and analysis of the same.

1.2 Objectives and Scope of the Study

The general objective of this thesis is to conduct experimental study on the flexural and compressive strengths of Jute Fibre-Reinforced concrete (JFRC) with the hypothesis that "reinforcing concrete with jute fibre significantly improves the flexural and compressive strength of concrete." In view of the general objectives, this thesis has the following specific objectives:

1. To carry out flexural and compressive strength tests on concrete reinforced with locally fabricated jute fibre.
2. To analyze the experimental results so as to determine the flexural and compressive strength properties of JFRC.

3. To assess the efficiency of the jute fibre as a reinforcement by evaluating the contribution in strength of the JFRC specimens.

In order to achieve the objectives, frame work of the experiment has been established with detailed checklists corresponding to the milestone activities. In doing so, literature survey has been made to assess previous works on the area of the thesis work and to get information about test specimen preparation, methods of testing and analysis of results. Following this, third-point bending tests were conducted on a simply supported beam specimens made from concrete mix with different jute fibre contents. Similarly, compression tests were carried out on cube specimens corresponding to the mixes utilized for each beam specimen.

After the accomplishment of the tests, observations and analysis of results were accomplished so as to assess the flexural and compressive strengths, and also to establish the relationship between different parameters. Finally conclusions and recommendations have been drawn based on the analysis results.

The thesis work is limited to investigate the effect of jute fiber reinforcement on compressive and flexural strengths of concrete. The scope is bounded to assess and analyze the compressive and flexural strengths on cube and beam specimens only. Further, the analysis is carried out on a particular species of natural fibre product, namely jute fibre. Therefore, the wide variety of morphological and chemical properties among the different natural fibres may affect the generality of conclusions and recommendations attained from the study. Since the study focuses on few aspects of the design parameters, only general insights on the design consideration of JFRC are dealt with in the thesis.

1.3 Contents of the Thesis

This thesis is intended to investigate and summarize the compressive and flexural strengths of JFRC. The thesis is organized into five sections. In section one are presented the background, objectives and scope of the study. Section two is devoted to the brief review of FRC. Section three aims at discussing the experimental study of JFRC. The

experimental set up, specifications of materials utilized in the experimental investigation, mix preparations, specimen casting and laboratory tests are all elaborated in this section. While in section four are dealt with discussions and analyses on the experimental results, in section five are presented a winding up conclusions and recommendations of the thesis work.

2 A BRIEF REVIEW OF FIBRE-REINFORCED CONCRETE

2.1 Historical Background of Fibre-Reinforced Concrete

Fibre Reinforced-Concrete (FRC) is one of the composite materials containing short discrete fibrous material uniformly distributed and randomly oriented, which increases its structural integrity. The concept of FRC technology dates back to the era of civilization. People used to employ mud reinforced with straw to construct houses, churches, mosques, utensils etc [5]. The recent trends in the technology of reinforcing concrete with fibres have been aiming at the improvement of physical properties, mechanical properties and to optimize cost of concrete production.

Different types of fibres have been considered as part of concrete making materials [8]: natural fibres, synthetic fibres and ferro-cementitious fibres. Peculiarities in using natural fibre reinforced concrete could be its economic benefits attributed to the ease of production with least energy, being environmentally friendly, high strength-to-weight ratio and allow insulation properties higher than current materials. The debating issue, apart from the advantages, is that natural fibres are biodegradable imparting negative effects on the performance of concrete [18]. This special concern of durability limits the range of applications of natural fibre-reinforced concrete to an extent dictated by engineering analysis.

2.2 Material Compositions for FRC

FRC comprises two components; namely the matrix component considered as the conventional concrete and the fibre component. The compositions of the concrete matrix component consist of cement, aggregate, water and in some cases additives are incorporated for a particular interest. The relative amount of these constitutive materials depends on several factors like workability, strength, durability and cost of the final product [3, 4, 9, 10].

2.2.1 Cement

Conventionally, cement is a powdered material that serves as a binder in mortar or concrete after reactions of lime or lime compounds have taken place with appropriate medium-usually water. Portland cement is one of such materials, composed largely of calcium and aluminum silicates, in which the former upon reaction with water produces the new compound capable of imparting stonelike quality to the mixture. While the specific gravity of Portland cement ranges from 3.12 to 3.16, its unit weight varies with the degree of compaction [4].

The chemical, physical and mechanical properties of cement are attributed to the basic constitutive compounds, the fineness to which the cement is ground and the ambient condition during the hardening process [1, 4]. The chemistry of cement is available elsewhere in literatures [2, 4]. In cement chemistry, it is customary to report the results of the chemical analysis in terms of the oxides of the elements present, although such compounds do not occur as oxides, nor do the oxides form the unit cell of the crystalline structure of the major cement compound. The basic constitutive elements are lime (CaO), silica (SiO₂), alumina (Al₂O₃), iron (Fe₂O₃ or FeO), gypsum (CaSO₄.2H₂O), magnesia (MgO), and alkalis (Na₂O) and K₂O). The characteristic compounds in Portland cement are shown in Table 2.1. The relative composition of the chemical compounds in Portland cement results in different types of cement such as normal Portland cement, high-early-strength cement, sulfate resisting cement etc, which could be meant for different purposes [2, 4].

Table 2.1 Names and Abbreviations of Major Compounds [4]

| Name | Chemical composition | Abbreviation |
|-------------------------------|---|-------------------|
| Tricalcium silicate | 3CaO.SiO ₂ | C ₃ S |
| Dicalcium silicate | 2CaO.SiO ₂ | C ₂ S |
| Tricalcium aluminate | 3CaO.Al ₂ O ₃ | C ₃ A |
| Tetracalcium alluminoferrite* | 4CaO.Al ₂ O ₃ .Fe ₂ O ₃ | C ₃ AF |

*The iron compounds may occur in a solid-solution system. C₃AF is only one of several compounds.

2.2.2 Aggregates

Aggregate is one component of FRC, which is connected into a cohesive whole by means of binding materials-the cement paste. Aggregates are usually inert materials or artificially manufactured from industrial products, which are added to cement paste in order to improve strength, durability and structural performance of concrete. Those aggregates from natural sources are conventionally adopted as concrete materials, and those from artificial ones are either light in weight or high density, developed for specific structural applications and also for solving part of the problems related to the shortage of naturally occurring aggregates. Aggregates can be explained with respect to petrological (rock type), mineralogical, and geological examinations, of which the later two basis are of great helpful in recognizing properties and qualities of aggregates for our purpose [1, 4].

The physical and mechanical properties of aggregate (density, strength, elasticity, toughness, hardness etc) depend largely on its composition, texture and structure. Such properties of aggregate and their contribution on its physico-mechanical properties, and also their influence on the strength of concrete are available in literatures [1, 2, 4]. The mechanical strength, bond characteristics and absorption capacity of aggregate are some of the factors that influence the strength of concrete. The bond is due, in part, to the interlocking of aggregate and to the paste that is attributed to the surface of the former. A rough surface and mineralogical heterogeneous particles result in better bond [1].

The common method to manufacture concrete is to obtain the aggregate in at least two size groups: the fine aggregate, which is not larger than 5mm (5/6 in); and the coarse aggregate, which comprises materials at least 5mm (5/6 in) in size. A further distribution of particle size is essential on one hand to improve the workability of fresh concrete and on the other hand to solve the economic problem related to the size of the aggregate. Some of the factors that govern the grading of aggregate are: the surface area of the aggregate, which determines the amount of water required to wet all the voids; the relative volume of the space occupied by the aggregate; the workability of the mix; and the tendency to segregate [1]. The grading is carried out using a method of sieve analysis

the procedure and requirements of which is detailed in the relevant codes of standards [1, 4, 29].

Aggregate is not fully inert material, as it was believed so far, hence its physical, thermal and chemical properties influence the performance of concrete [1]. Such influences are more pronounced in the case of FRC made with natural fibres since natural fibres could undergo chemical reaction with the aggregate resulting undesirable features on concrete. Also, there are deleterious substances that may be found in aggregate [1, 4]:

Impurities- interfere with the process of hydration of cement. Examples of such impurities are organic impurities.

Coatings-prevent the development of bond between aggregate and cement paste. These include clay and other fine materials.

Unsound (weak) materials-certain materials of the aggregate themselves may fail to maintain their integrity or lead disruptive expansion on freezing or even exposure to water.

Alkali-aggregate reaction-such deleterious reaction starts with the attack on the siliceous minerals in the aggregate by the alkaline hydroxides derived from the alkalies (Na_2O and K_2O) in the cement, resulting the formation of an alkali-silicate gel and alteration of the borders of the aggregate. Swelling of the gel is not limited and takes in water with a consequent tendency to increase volume.

2.2.3 Water

In the production of concrete, water is used for mixing, washing of aggregate and curing of the final concrete product. Mixing water should contain no substances that can have an appreciably harmful effect on the process of hydration or upon the durability of concrete during its service period. Water having appreciable amounts of impurities-silt, oil, acids, alkalies, salts of alkalies, organic matter and sewage may have an injurious effect upon concrete [4].

The reduction in strength of concrete through the use of water suspected of undesirable substances could be as high as 10% [29]. The effect of same amount of impurities in water for washing aggregate is much greater than that of mixing water. Such water if used for washing aggregate causes deleterious coatings (silts, salts or organic materials) on the surface of aggregate particles. Water containing sufficient amount of acidic or organic substances should be regarded with suspicion to be used for curing of concrete. Nevertheless, silt or oil in curing water does not appear to have harmful effects except for the possibility of discoloration [4]. Above all, the limiting amount of deleterious substances to be employed in making natural fibre reinforced concrete should not be underestimated, as the natural fibres by themselves are highly susceptible to such impurities. ASTM C 1116-02 gives the limiting values of deleterious materials in water for the FRC.

2.2.4 Fibres

A fibre may be defined as a flexible, macroscopically homogenous body having a high ratio of length to width and a small cross-section [5, 6]. On the basis of their origin, fibres are classified as follows [5]:

Natural fibres-are those derived directly from the animal, vegetable and mineral kingdoms. These include cotton, linen, hemp, jute and ramie all obtained from vegetable cellulose; wool, mohair, vicuna from animal; and asbestos from minerals.

Synthetic fibres- are manufactured from natural organic fibres, synthetic organic polymers and inorganic substances. Included in this category are: rayon, acetate, azlon based on natural organic polymers; acrylic, aramid, nylon, olefin, polyester, vinyon based on synthetic polymers; and glass, metallic fibres, ceramics based on inorganic substances.

Fibres have been used for the manufacture of a wide variety of products in different fields of applications in fine arts, flooring materials, food science, forensic aspects, furniture and fracture (fatigue) mechanics [6]. The detail discussions of fibre types, their properties, methods of productions and applications are available in literatures [5, 6] and

only a few aspects of vegetable fibres relevant to the present study are reviewed subsequently.

The concept of applying vegetable fibres for commercial and domestic uses dates back to the ancient Egypt (4000BC)-ropes, cords, and fabrics were made from reeds and grasses; boats, sails and mats were made from palm leaf fibres and papyrus stalks from the pith section. Jute was cultivated in India in ancient times and used for spinning and weaving. These days, jute is mainly used for sacking, balling for rugs, webbing and twine [5].

Vegetable fibres are derived from the different sources of plants: bast fibres extracted from the bark of certain plants; leaf fibres (hard fibres) used for cordage; seed-hair fibres (cotton); and palm fibres (brush fibres) from various section of the plant. The principal chemical composition of vegetable fibres is cellulose mostly bound by a natural gummy substance closely associated with lignin. While all vegetable fibres have cellulose as a major chemical component, other components like hemicelluloses, pectins, extractives and lignin vary significantly providing the characteristics of specific fibres as shown in Table 2.2 [5, 6].

Table 2.2 Chemical Composition of Common Vegetable Fibres [5]

| Fiber | Cellulose | Hemicellulose | Pectin | Lignin | Extractives |
|--------------|------------------|----------------------|---------------|---------------|--------------------|
| Cotton | 94.0 | 2.0 | 2.0 | - | 2.0 |
| Kapok | 43.2 | 32.4 | 6.6 | 15.1 | - |
| Flax | 71.2 | 18.5 | 2.0 | 2.2 | 6.0 |
| Hemp | 74.3 | 17.9 | 0.9 | 3.7 | 3.1 |
| Ramine | 76.2 | 14.5 | 2.1 | 0.7 | 6.4 |
| Jute | 71.5 | 13.3 | 0.2 | 13.1 | 1.8 |
| Abaca | 70.0 | 21.8 | 0.5 | 5.7 | 1.8 |
| Sisal | 73.2 | 13.3 | 0.9 | 11.0 | 1.6 |

From Table 2.3, one can see that bast and leaf fibres have higher tensile strength and modulus of elasticity, but lower in extensibility than cotton. Besides, vegetable fibres are stiffer but less than synthetic fibres [6].

Table 2.3 Mechanical Properties of Vegetable Fibres [6]

| Fibre | Fineness, km/kg | Tensile strength ^a, km | Elongation, % | Modulus of elasticity^b, N/tex | Modulus of rapture, mN/tex |
|---------------------------|----------------------------|--|--------------------------|---|---|
| <i>Bast (soft) Fibres</i> | | | | | |
| flax | - | 24-70 | 2-3 | 18-20 | 8-9 |
| hemp | 139 | 38-62 | 1-6 | 18-22 | 6-9 |
| jute | 489 | 25-53 | 1.5 | 17-18 | 2.7-3 |
| kenaf | 180 | 24 | 2.7 | - | - |
| ramie | - | 32-67 | 4.0 | 14-16 | 11 |
| urena | 342 | 16 | 1.9 | - | - |
| <i>Leaf (hard) fibres</i> | | | | | |
| abaca | 32 | 32-69 | 2-4.5 | - | 6 |
| cantala | 58 | 30 | - | - | - |
| henequen | 32 | 20-42 | 3.5-5 | - | - |
| istle | 34 | 22-27 | 4.8 | - | - |
| phormium | 38 | 26 | - | - | - |
| sansevieria | 118 | 43 | 4.0 | - | - |
| sisal | 40 | 36-45 | 2-3 | 25-26 | 7-8 |
| <i>Seed hair</i> | | | | | |
| kapok | - | 16-30 | 1.2 | 13 | 10 |
| <i>Others</i> | | | | | |
| coir | - | 18 | 16 | 4.3 | 16 |

^a Based on breaking length, which measures strength per unit area

^b Young's modulus

Although the uses of vegetable fibres for indoor applications have been justified, distinct features of vegetable fibres when combined with concrete have not been well developed. With this regard, recent attempts have been made to practice vegetable fibres as a component material of concrete. Concrete reinforced with sisal fibre, coir fibre and others have been studied [9, 10, 13].

Primarily, fibres in FRC serve as crack arrestors thereby increase post cracking properties, improve fatigue and fracture properties, control plastic shrinkage cracking, lower the permeability of concrete and thus reduce bleeding of water. Not all fibres play the same role on concrete properties-some types of fibres induce greater impact, abrasion and shatter resistance while others may reduce strengths [24, 25, 27]. If fibres are added beyond the permissible amount, they may result a problem in workability of fresh FRC. A peculiarity in natural fibre reinforced concrete is that durability of concrete will be in question under severe exposures which may degrade the fibres on account of their chemical composition and molecular structure [18, 20, 26].

2.2.5 Admixtures

Admixtures are materials other than the main constituents of concrete that are added to the mixing process at appropriate periods and conditions, thus mainly modify the hydration reaction so as to introduce a significant change in behavior of concrete production-the out come of the changes follows the intended functions. A number of admixtures that have been in practice in ordinary concrete work include accelerators, retarders, water reducers, air-entraining agents, gas-forming admixtures, expansion producing admixtures, bonding admixtures, curing aides etc [1, 4]. Those additives employed for the conventional concrete could be adopted for the FRC with the relevant modifications associated with the chemical and morphological properties of a particular fibre utilized in making the FRC. In addition, special polymeric resins have been exercised to improve the chemical, physical and mechanical properties of natural fibre reinforced-concrete [5, 6].

The various purposes of admixtures are to improve workability of fresh concrete, reduce water requirement, improve durability by entrainment of air, accelerate hardening so a to produce high-early strength, aid curing, impart water proofing, retard setting, improve wear resistance (hardness), reduce offset shrinkage during setting and hardening, offset or reduce some adverse chemical reactions, reduce bleeding and the evolution of gases and so on [4].

It is worth noting that a specific type of admixture can be effective for its intended purpose while it may have an adverse effect on any other important properties of the fresh or hardened concrete. Therefore, the proceeding factors, more emphasized in the case of FRC, should be closely examined to decide whether or not an admixture is desirable or necessary [4, 14, 15]:

- (1) the possibility of accomplishing the desired result by a small modification in the basic mix
- (2) the additional cost of using admixture against the additional cost of a modified basic mixture
- (3) the possible adverse effects on properties other than those which the admixture is intended to improve.

2.3 Mix Design of the FRC

Mix design is the process of determining the relative quantities of the ingredients of concrete taking in to account the availability of materials and their cost, requirements of placing and finishing the fresh concrete, and properties of the hardened concrete[1, 4, 19]. The mix design of FRC materials is quite similar to that of the conventional concrete except the inclusion of reinforcing fibres-the relative amount of which is governed by workability of the fresh concrete and the properties of the hardened concrete [26, 29].

The economic aspect of concrete mix in construction depends primarily on the cost of material other than on cost of labor and related factors as the later two, although take larger part of the total cost, do not make differences between different concretes. Hence, concrete mix design aims at compromising between the costs of materials associated with the amount needed in the desired mix and the production of appropriate workability so as to keep placement and finishing costs at a minimum while securing quality in the finished product [1, 26].

In practice, proportion of cement, fine aggregate and coarse aggregate is expressed in terms of parts or ratios with cement as a reference-usually taken as unity. The content of water, fibre and other entrained air or admixtures is expressed in terms of water-cement

ratio, fibre-matrix ratio and percentage ratio respectively. In any case, the basis of proportioning should be stated along with the parts or ratios: may be either by weight or by volume (absolute or bulk) [3, 4].

In ordinary concrete mix, it is reasonable to assume that concrete consists essentially of inert mineral aggregate and cement-water paste which is the active ingredient controlling workability, strength, permeability and drying shrinkage [1, 4]. However, this assumption is not always valid in FRC, as the content and anatomy of the fibre component would significantly affect properties of fresh and hardened concrete [5, 18].

Water-cement ratio, cement content or cement-aggregate ratio, gradation of the aggregate and consistency of the paste are among the variables to be manipulated in the mix design of concrete [1]. In addition, the content and morphology of fibre in FRC have to be taken into account while mix design is carried out. All the aforementioned variables are so interrelated that one can not choose or manipulate arbitrarily; usually two or more of the variables are specified and others are adjusted to give the intended requirements dictated by general experience with regard to structural design considerations, durability and condition of placing.

Different methods of mix design of concrete have been investigated so far [4]: arbitrary proportions, proportioning by maximum density of aggregate, proportioning by surface area of aggregate, proportioning by fineness modulus of aggregate, proportioning by void content ratio and mortar voids, and proportioning by void contents of coarse aggregate. There are no separate methods of proportioning devised for the mix design of FRC. Instead, the relative amount of cement, aggregate and water is determined based on the usual methods of proportioning, then follows the determination of the fibre content based on the required workability and strength of the FRC. Many investigations [3, 9, 11, 26] have been undertaken to determine the relative amount of fibre and the fibre aspect ratio to be added in FRC that would result a sound workability and desired properties of hardened concrete.

The amount of fibre to be added in a concrete mix is measured as a percentage of the total volume of the composite (concrete and fibres) termed volume fraction (V_f), and the aspect ratio (l/d) is calculated by dividing fibre length (l) by its diameter (d). If the fibre in question has non-circular cross section, an equivalent diameter can be used to calculate aspect ratio. Generally, the fibre content and aspect ratio of the additive fibre should be lower in order to have a good workability [3, 26].

2.4 Properties and Test Methods of FRC

2.4.1 General

The distinct features of fibre reinforced-concrete such as strength, durability, permeability, creep and shrinkage have been studied [9-18]. Besides, several test methods have been explored and reported by various institutions and codes of practices including ACI and ASTM [19, 29]. It is not possible to put dead ends to the over all properties and test methods of FRC as there are some concerns of FRC that got a debating issue among several endeavors. Consequently, it appears sound to point out only some aspects of such subjects through the subsequent paragraphs.

2.4.2 Properties of FRC

The contribution of fibres to the compressive strength is usually at the early age of concrete, the case of which is more prominent to natural fibres [10, 22]. However, the compression strength could be improved at extended ages by extracting the crystalline (mineral) portion through a further processing of the fibres [30].

Under compressive loading the microcracks in the solids come under a local tension at their tips causing wide and unstable crack propagation due to the interaction between other micro-cracks. When fibres are present in such a body, they affect the crack propagation by increasing the resistance to sliding of the initial microcracks and opening of the wing cracks by crack-bridging [22]. This phenomenon signifies that fibres can be exploited to increase the compressive strength in a manner analogous to the tensile crack-bridging and in consequence provide a passive confining pressure.

B. Chatveera et al [9] have shown that sisal fibre-reinforced composite containing rice husk ash provides better strength both in compression and flexure. It was also indicated that the combination of using sisal fibre reinforcement and rice husk ash can improve the ductility of the composites. Further, Li et al [31] reported that an optimum addition of natural hemp fibre increases the compressive and flexural properties of natural hemp fibre-reinforced concrete.

Plain concrete is weak in tension, and the limiting tensile force is carried between cracks. When fibres are added to the plain concrete, the tension capacity is increased through the transfer of tensile forces at the cracks by fibre interferences. In addition to the increase in tensile strength capacity, fibres can reduce crack width with further improvement in the rigidity of the FRC [10, 24].

The tensile strength of FRC made with high tensile fibres largely depends on the pullout resistance between the fibre and matrix. This interfacial bond between the fibre and the matrix can be improved through chemical treatment of the fibre or physical manipulation over the geometry of the fibre [21, 23, 26, 28, 32]. Alva et al [23] have shown that crimping yarns results in strain hardening composite with a marked increase in adhesion and frictional resistance. Further, Guozhong Li et al [28] reported that cotton stalk fibre treated with styrene acrylic emulsion can form a flexible interfacial layer between the fibre and matrix, which is stronger than the matrix and relaxes the additional stress in course of shaping.

The flexural strength and deformation characteristics of concrete beams reinforced with various fibres have been studied [11, 27, 31]. Flexural tests of mortars reinforced with different steel wool contents dictate that there was about 36% increase in flexural strength of the FRC. Collapse of such beams during testing occurred mostly through either flexural failure of concrete in compression or diagonal tension with out brittle modes of failure. The fibres control the propagation of major cracks, thus preventing sudden collapse. Experiments using concrete reinforced with soft fibre (glass or sisal) revealed that the crack expanding resistance and flexural toughness of plain concrete could be enhanced through the addition of fibres [9, 10, 11]. The flexural strength of

laminates in sandwich construction can be significantly increased using a reformed bamboo plate as a tensile layer and fibre reinforced-mortar sheet as a compression layer. The high-strength to weight-ratio of bamboo fibres accounts for the improved in mortar strength and the reduced in total weight of the laminate [27].

Fibre reinforced-concrete has an important behavior of absorbing enormous amount of energy. There can be as much as 100% increase in flexural toughness with the inclusion of natural hemp fibre and coir fibres [10, 31]. Apart from the increase in toughness and ductility, the increase in post-cracking strength with the incorporation of fibres maintains the equilibrium and structural integrity of the whole system [10, 13].

The development of diagonal tensile cracking in the direction perpendicular to the principal tensile stress axis rapidly softens crack surfaces, which significantly reduces the shear strength of the beam. This asserts that the shear failure of a reinforced concrete beam is directly related to the diagonal tensile cracking and flexural deformation. Since FRC has the ability to develop post-cracking tensile strength, the applied shear force is resisted by both the compression and the tension zone. Thus, the overall shear strength can be defined as the sum of the contributions of both compression and tension zones [12].

2.4.3 Test Methods for FRC

Development of testing methods for FRC is not a dead end and the issue is still in progress. Around in the 1970s, there have been some organizations involved in the development of test methods for FRC [19].

ACI Committee 544 and ASTM [19, 29] provide the following suggestions for rheology, compression and flexural test of FRC.

Material Specifications

Material specification for cement, aggregate, water and admixture are similar to the conventional concrete. In reference to this study, conventional concrete signifies the

usual concrete which contains cement, water and aggregates as a basic constituents whereas FRC contains additional fibrous components. ASTM C 1116 recommends that natural fibre should be approved for their adverse effects during reaction with the constitutive materials and surrounding environment in the cracked matrix [29].

Specimen Preparation

Generally, external vibration using a standard amplitude, frequency and duration, as described in ASTM C 192, is suggested for all sample preparation in the laboratory [29]. Although internal vibration is not recommended for FRC because of the effect of fibre orientation and lack of consolidation in stiff mix, it may be used for specimens with least dimensions greater than about 102mm reflecting the actual practice in the field. It is also concluded that external vibration promotes preferential fibre alignment and increases the toughness strength [19].

Compressive Strength

Compression test for FRC can be conducted as per the conventional concrete stipulated in ASTM C 39, C 192 and C 469.

Workability

Workability is the property of fresh concrete which indicates its ability to be mixed, handled, transported and placed with a minimum loss of homogeneity [4, 19]. The slump cone test may be used as an indication of relative workability of FRC, however, other test methods, the Vebe and Inverted cone tests are preferred. This is due to the fact that the presence of fibre makes the concrete easily consolidate and hence reduces the slump [29].

Flexural Strength

The general test procedures in ASTM C 42, C 78, C 293 and C 683 are applicable with the subsequent constraints:

- The span of FRC specimen shall be at least 50mm greater than three times the depth and in any case not less than 350mm.
- Width and depth of the specimens should be at least three times the maximum fibre length and the maximum size of aggregate used.

- Recommended size for thick section is 150*150*350mm.

The flexural behavior of FRC can be determined by evaluating the modulus of rupture, first-crack strength and flexural toughness indices from the test results. According to ASTM C 1018, the end point deflection for a toughness index, I_n is $(n+1)/2$ times the first-crack deflection. The selection of most appropriate index so as to measure material performance for a specific application depends on the level of serviceability required in terms of cracking and deflection. Hence, when the level of serviceability appropriate to the particular application in terms of cracking and deflection indicates that the specified end-point deflection should be higher, a higher index value shall be used. For most practical applications, index values of 5.0, 10.0 and 20.0 corresponding to I_5 , I_{10} and I_{20} respectively, dictates elastic linear behavior up to first-crack and perfectly plastic thereafter [19, 29].

Other parameters called residual strength factors could be derived directly from toughness indices to describe the level of strength retained after first crack. These factors can be derived simply by expressing the average post-crack load over a specified deflection interval as a percentage of the load at first crack. Note that there is no restriction on the representations and calculations of the toughness indices; the requirement is to specify the end point deflection as a multiple of the first-crack deflection that is consistent with the intended conditions of serviceability [29].

The first-crack deflection for third-point loading test can be estimated, assuming elastic linear behavior up to the first crack, by [29]:

$$\delta = 23 \frac{PL^3}{1296EI} * \left[1 + \frac{216D^2(1+\mu)}{115L^2} \right] \quad (2.1)$$

Where P is the first crack load,

L is span length,

E is the estimated modulus of elasticity of the concrete,

I is the cross-sectional moment of inertia,

D is depth of specimen and
 μ is Poisson's ratio.

The method of obtaining the modulus of rupture of FRC is similar to that of conventional concrete [29]. Thus, if fracture occurs in tension surface within the middle third of span length, then the modulus of rupture, f_r , can be determined by:

$$f_r = \frac{PL}{bh^2} \quad (2.2)$$

If fracture occurs in tension surface outside of the middle third of span length by not more than 5% of the span length, then the modulus of rupture can be determined by:

$$f_r = 3 * \frac{P * a}{bh^2} \quad (2.3)$$

The test result will be discarded if fracture occurs in the tension surface outside of the middle third of the span by more than 5% of the span length.

3 EXPERIMENTAL STUDY OF JFRC

3.1 Experimental Set Up

The experimental investigation carried has involved two major tasks: material specifications and experimental evaluation of JFRC. Materials required for the experimental works were prepared and also their properties were determined in the laboratory. Compressive and flexural strengths of the FRC were evaluated by conducting tests in the laboratory. The general laboratory set up for the thesis work is presented schematically in Figure 3.1 and Figure 3.2.

The material and test specimen preparation include washing and sieve analysis of aggregates; determination of specific gravity, absorption capacity, and unit weight of aggregates; cleaning and chopping of fibres; determination of tensile strength of fibres; measurement of the required amount of mix ingredients; mix preparations and evaluation of properties of the fresh FRC; and test specimen preparations. The detail descriptions of the equipment utilized and the procedure followed during the accomplishment of these activities is described in appendix-A.

An ADR-Auto Range testing machine has been employed to carry out the compression test. The general description of the test set up is in accordance with the manufacturer instructions-ELE. The test set up comprised compression test frame and an ADR-Auto console.

The loading frame component consists of an upper platen assembly, lower platen assembly, ram extension with a connection plug to the console and enclosure of the loading assembly as shown in Figure 3.1. The upper platen assembly is equipped with a ball seated platen to which the upper rectangular platen and ram extension is fitted and the lower platen assembly is supplied with the lower most rectangular platen, adaptor, distance pieces and self-centered lower platen on which the sample is to be placed. The self-centered platen is provided with locating pillars to enable test specimens to be accurately located to the loading axis of the machine.

The console component controls the automatic loading cycle by the closed loop micro-processor (hydraulic system). All control functions and displays are built into the hydraulic power pack of the console. The front panel of the console consists of an LCD display, a key pad and four function keys-"RUN", "STOP" and "RESET" by which the operations of the ADR-Auto are controlled. Several operating modes are possible by the ADR-Auto configurations: display units, pace control mode, automatic sample log, automatic sample print, automatic load tare, auto-increment reference, option for dual pace rate, failure threshold, failure detection, sample selection, clock setting, reset mode, calibration and other testing facilities. The rear panel of the console is fitted with an AC power input, Travel Limit Switch and a serial port.

While the micro-processor runs a series of self-test routines to check the operation of the system, a serial output port that is built into the system enables test data to be stored in memory, downloaded to a PC or suitable printer.

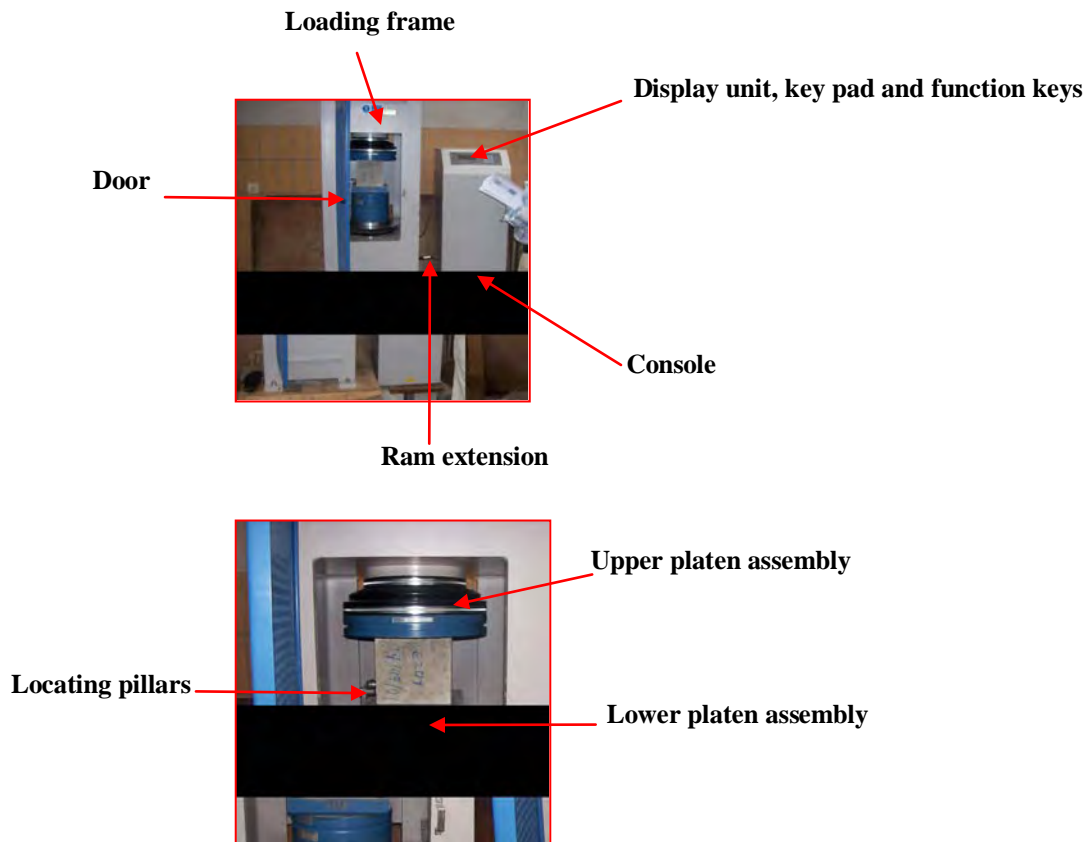


Figure 3.1 Compression Test Set Up

The flexural test set up consists of a microprocessor controlled Universal Testing Machine with model UTM 70-C 0820/C as shown in Figure 3.2. The general description of the test set up is in accordance with the manufacturer instructions-ELE. The UTM machine comprises two major components: the machine frame and the control console.

The machine frame is bolted to the ground with a steel base plate and it contains a piston (cylinder assembly) that incorporates electronic load cell and mobile frame. The mobile frame is manipulated with four high tensile strength steel columns, upper crosshead directly connected to the piston and an intermediate crosshead with supporting platen. The two point loading accessory is connected to the loading cell and a supporting device is placed on the frame platen on which beam specimens are to be placed. The vertical position of the supporting system can be adjusted by independent auxiliary cylinders controlled by pendent hand control.

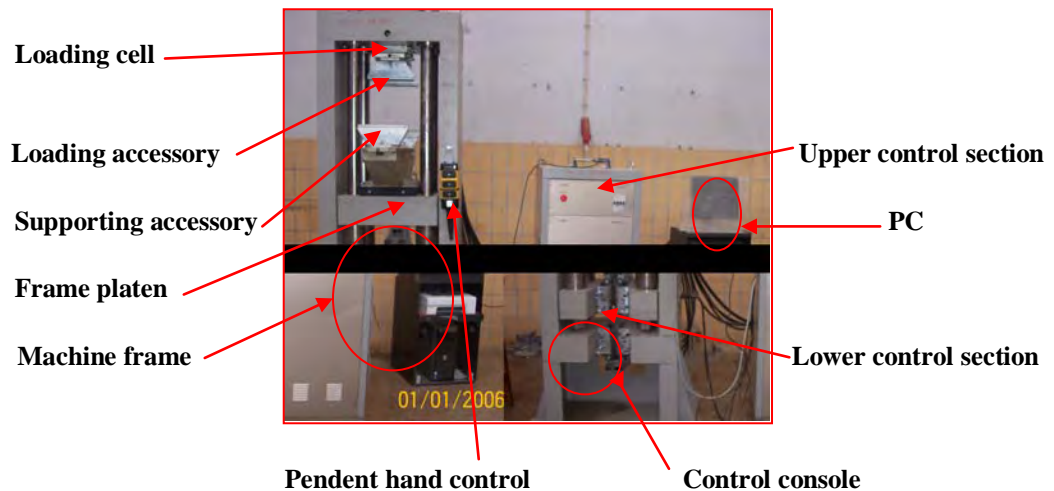


Figure 3.2 Bending Test Set Up

The lower section of the control console houses the hydraulic assembly which comprises hydraulic pump, proportional valve, hydraulic valves, heat exchanger to control the oil temperature and an oil tank. The upper part of the control console houses the electronic microprocessor control driven by a PC. The control console is principally used to condition and convert all the analogical signals to send to the PC, control the valves and

safety devices, automate the test, maintain constant load rate and interacts with the PC to control the test conditions.

Upon operating a test on the UTM, the hydraulic pump located in the control console increases the pressure in the cylinder assembly of the machine and moves the mobile part of the frame, thus applying load to the specimen up to failure which is recorded on the display unit on the PC.

3.2 Material Specifications

3.2.1 Water

Tap water from the municipal water mains of Addis Ababa City was utilized to wash aggregates, to mix concrete and to cure the test specimens. None of the impurity contents of the water were determined.

3.2.2 Cement

In order to minimize the effect of high rate of hydration on the jute fibre, Pozzolana Portland Cement (PPC) from Mugger Cement Factory was used for the concrete mix. Neither the physical nor the chemical properties of the cement under consideration were investigated.

3.2.3 Aggregates

Natural river sand and crushed gravel dampened in the laboratory months ago were utilized for the test. The aggregates were washed and dried. Before stepping on to other works, sand and gravel were sieved with 4.75mm and 25mm sieves respectively and the materials retained were rejected. Then, the aggregates were sieve analyzed following the procedures established in Table A-1 and the results are presented in Figure B-1 and Figure B-2.



Figure 3.3 Material Preparation

For the determination of the specific gravity, absorption capacity, and compacted unit weight of aggregates, the general procedures outlined in Table A-2 and Table A-3 of Appendix-A were applied in the laboratory and the results are shown in Table 3.1.

Table 3.1 Specific Gravity, Absorption Capacity and Unit Weight of Aggregates

| Aggregate | Bulk specific gravity | Bulk specific gravity (SSD) | Apparent specific gravity | Absorption capacity (%) | Unit weight (kg/m ³) |
|-----------|-----------------------|-----------------------------|---------------------------|-------------------------|----------------------------------|
| Sand | 2.38 | 2.47 | 2.62 | 3.95 | 1560 |
| Gravel | 2.69 | 2.75 | 2.84 | 1.90 | 1600 |

3.2.4 Fibre

The type of fibre that has been considered in the experimental investigation was jute fibre manufactured in the Sidama Administrative Zone.

Jute is one of the bast fibers obtained from herbaceous annual plants- white *Corchorus Capsularis* originally from Asia having round seed pod and *C. Olitorius* originally from Africa having a long pod.

The manufacturing process of jute fibre involves hand harvesting of the source plant, drying in the field for defoliation, retting for periods up to a month, stripping and sun drying. Further formation and grading of the jute fibre under consideration for color, length, fineness, strength, cleanliness, luster, softness and uniformity is possible depending on the requirements stipulated by specific uses [6].

The tensile strength and extensibility of jute fibre were determined in the laboratory using texture analyzer. The texture analyzer was fixed at a span of 150mm height, the fibre was tied on the top and bottom jaws of the analyzer and load was automatically applied on the fibre. The breaking load and extension were recorded by the Jaxter software installed in the PC that was connected to the analyzer. The tensile stress was calculated by dividing the ultimate load by the cross-sectional area of the fibre and the results are shown in Table 3.2.

Table 3.2 Tensile Strength and Extensibility of Jute Fibre

| S/No | Cross-section (mm) | | Area (mm ²) | Breaking Load (N) | Extension (mm) | Stress (MP) | Extensibility (%) |
|-----------------------|-----------------------|-------|----------------------------|----------------------|-------------------|----------------|----------------------|
| | Width | Depth | | | | | |
| 1 | 0.11 | 0.36 | 0.0396 | 19.10 | 2.50 | 482.32 | 1.67 |
| 2 | 0.22 | 0.22 | 0.0484 | 21.00 | 3.00 | 433.88 | 2.00 |
| 3 | 0.16 | 0.29 | 0.0464 | 23.00 | 1.50 | 495.69 | 1.00 |
| 4 | 0.13 | 0.27 | 0.0351 | 17.00 | 2.00 | 480.23 | 1.33 |
| 5 | 0.10 | 0.36 | 0.0360 | 14.80 | 2.00 | 411.11 | 1.33 |
| 6 | 0.22 | 0.24 | 0.0528 | 20.50 | 2.00 | 388.26 | 1.33 |
| Average-values | | | | | | 448.58 | 1.44 |

The fibre was first cleaned and chopped to a length of 30-50mm [13]. Thereafter, the required amount of fibres for each batch was weighed and added to the concrete matrix during the mixing process.

3.3 Mix Proportioning and Specimen Preparations

3.3.1 Mix Proportioning

The mix proportioning for this experimental work has been carried out following the ACI method of mix proportioning. The material data for sand and gravel were those values determined in the laboratory in section 3.2.3 above, and the values for cement and jute fibre were taken from literatures [4, 6].

A. Mix Information

(1) Desired strength is 20MPa.

(2) Expected slump for medium workability is 20-50mm [33].

(3) Materials

- Cement Specific gravity = 3.15
- Sand Dry unit weight = 1560kg/m^3
Dry bulk specific gravity = 2.38
Fineness modulus = 3.00
Absorption capacity = 3.95%
- Gravel Dry unit weight = 1600kg/m^3
Dry bulk specific gravity = 2.69
Fineness modulus = 6.78
Absorption capacity = 1.9%
Maximum aggregate size = 20mm
- Jute fibre Dry unit weight = 1500kg/m^3
Absorption capacity = 14% to bring the jute fibre to SSD [6]

B. Mix Proportioning

- (1) The maximum amount of water for a slump of 20-50mm and maximum aggregate size 20mm, including allowance for absorption by aggregates is 184kg per cubic meter of concrete [4].
- (2) The approximate volume of entrapped air for non-air entrained concrete with maximum aggregate size of 20mm is 2% [4].
- (3) Minimum cement content for C-20 concrete with maximum aggregate size of 20mm is 290kg per cubic meter of concrete [33].
- (4) Maximum water-cement ratio, from durability requirement, for moderate condition of exposure and maximum aggregate size of 20mm is 0.62 [33].

Maximum water-cement ratio, from strength requirement, for concrete with 20MPa strength is 0.60 [4].

Taking the minimum of the two values; water-cement ratio to be used for the mix design is 0.60. Thus, the cement content is:

$$\frac{184}{0.60} = 307 \text{ kg/m}^3 > 290 \text{ kg/m}^3 \dots\dots\dots \text{ok}$$

- (5) Bulk volume of dry rodded gravel for maximum aggregate size of 20mm and fineness modulus of sand 3.00, is 0.59m³ per cubic meter of concrete [4].

Hence, the dry mass of gravel per cubic meter of concrete is:

$$0.59 * 1600 = 944 \text{ kg.}$$

- (6) The absolute volume of mix ingredients per cubic meter of concrete is:

$$\text{Cement} = \frac{307}{3.15 * 10^3} = 0.097 \text{ m}^3$$

$$\text{Water} = \frac{184}{1.00 * 10^3} = 0.184 \text{ m}^3$$

$$\text{Gravel} = \frac{944}{2.69 * 10^3} = 0.351 \text{ m}^3$$

$$\text{Air}(2\%) = 0.02 * 1.00 = \underline{0.020 \text{ m}^3}$$

$$\text{Total volume without sand} = \underline{\underline{0.652 \text{ m}^3}}$$

Volume of sand = $1.000 - 0.652 = 0.348\text{m}^3$ and the dry mass = $0.348 * 2.38 * 10^3 = 828\text{kg}$.

Therefore, the mass of ingredients per cubic meter of concrete on dry weight basis is:

Cement = 307kg

Water = 184kg

Sand = 828kg

Gravel = 944kg

Adjustment of the quantities is made for absorption by aggregates. Thus,

Cement = 307kg

Water = 134kg

Sand = 860kg

Gravel = 962kg

(7) The mass of constituent materials per cubic meter of JFRC for different jute fibre content is determined as follows.

- **1% by volume of jute fibre**

Volume of jute fibre per cubic meter of concrete = 0.01m^3 .

Volume of the concrete matrix = $1.00 - 0.01 = 0.99\text{m}^3$.

Thus, the modified mass of constituent materials per cubic meter of concrete, for 1% fibre content is:

Cement = $307 * 0.99 = 304\text{kg}$

Sand = $860 * 0.99 = 851\text{kg}$

Gravel = $962 * 0.99 = 952\text{kg}$

Fibre = $0.01 * 1500 = 15\text{kg}$

Water = $134 * 0.99 + 15 * 0.14 = 135\text{kg}$ (including 14% absorption by jute fibre)

The mix proportions for other fibre contents were carried out in a similar fashion and the results are shown in Table 3.3 below.

Table 3.3 Mix Quantities per Cubic Meter of Concrete for Different Fibre Contents

| Mix materials | Mass of materials per cubic meter of concrete (kg) | | | |
|---------------|--|-------|-------|-------|
| | 0.00% | 0.25% | 0.50% | 1.00% |
| Cement | 307 | 306 | 306 | 304 |
| Water | 134 | 135 | 135 | 135 |
| Gravel | 962 | 960 | 957 | 952 |
| Sand | 860 | 858 | 856 | 851 |
| Fibre | 0 | 4 | 8 | 15 |

3.3.2 Mix and Test Specimen Preparations

The required proportions of mix ingredients obtained in section 3.3.1 were weighed for each batch separately. Then, gravel was spread in an even layer in the mixing pan followed by cement and sand respectively. Some amount of fibre was added on each top of ingredient. After 1 minute dry mixing, water and the remaining fibre were added and the mixing operation continued for more than 3 minutes (since FRC requires more mixing period than ordinary concrete [29]). During the mixing process, some properties of the fresh concrete were diagnosed and the observations are shown in Table 4.1.

After the mixing operation had been completed, a total of 30 specimens of which 15 for compression test and 15 for flexure test were prepared and cured in moist storage for 28-days. The detail procedures for the mixing of concrete and specimen preparation are described in Table A-4, Table A-5 and Table A-6 of appendix A.

Moreover, Table 3.4 depicts the test programme for the thesis work. In the specimen coding C, B and J represents cube, beam and jute fibre respectively. In addition, the first and second numbers in the coding stand for the test series and specimen number of that particular test, respectively.

Table 3.4 Test Programme

| Test series | Code | Specimen size (mm) | | | Test | Fibre | Fibre content (%) |
|-------------|--------|--------------------|-------|-------|-------------|-------|-------------------|
| | | Length | Width | Depth | | | |
| 1 | CJ 1-1 | 150 | 150 | 150 | Compression | Jute | 0.00 |
| | CJ 1-2 | 150 | 150 | 150 | Compression | Jute | 0.00 |
| | CJ 1-3 | 150 | 150 | 150 | Compression | Jute | 0.00 |
| | BJ 1-1 | 500 | 100 | 100 | Flexure | Jute | 0.00 |
| | BJ 1-2 | 500 | 100 | 100 | Flexure | Jute | 0.00 |
| | BJ 1-3 | 500 | 100 | 100 | Flexure | Jute | 0.00 |
| 2 | CJ 2-1 | 150 | 150 | 150 | Compression | Jute | 0.25 |
| | CJ 2-2 | 150 | 150 | 150 | Compression | Jute | 0.25 |
| | CJ 2-3 | 150 | 150 | 150 | Compression | Jute | 0.25 |
| | BJ 2-1 | 500 | 100 | 100 | Flexure | Jute | 0.25 |
| | BJ 2-2 | 500 | 100 | 100 | Flexure | Jute | 0.25 |
| | BJ 2-3 | 500 | 100 | 100 | Flexure | Jute | 0.25 |
| 3 | CJ 3-1 | 150 | 150 | 150 | Compression | Jute | 0.50 |
| | CJ 3-2 | 150 | 150 | 150 | Compression | Jute | 0.50 |
| | CJ 3-3 | 150 | 150 | 150 | Compression | Jute | 0.50 |
| | BJ 3-1 | 500 | 100 | 100 | Flexure | Jute | 0.50 |
| | BJ 3-2 | 500 | 100 | 100 | Flexure | Jute | 0.50 |
| | BJ 3-3 | 500 | 100 | 100 | Flexure | Jute | 0.50 |
| 4 | CJ 4-1 | 150 | 150 | 150 | Compression | Jute | 1.00 |
| | CJ 4-2 | 150 | 150 | 150 | Compression | Jute | 1.00 |
| | CJ 4-3 | 150 | 150 | 150 | Compression | Jute | 1.00 |
| | BJ 4-1 | 500 | 100 | 100 | Flexure | Jute | 1.00 |
| | BJ 4-2 | 500 | 100 | 100 | Flexure | Jute | 1.00 |
| | BJ 4-3 | 500 | 100 | 100 | Flexure | Jute | 1.00 |

3.4 Experimental Tests

3.4.1 Compression Test

The compression test was conducted on cube specimens cured for 28 days. The test cubes were removed from the moist storage 24 hours before testing. The top and bottom bearing plates of the compression testing machine were wiped and cleaned before the placement of the specimen. After ensuring the connection between the loading and control chambers, the cube specimen was placed on the lower bearing plate keeping the center alignment by the screwed guides on the bearing plate.

The door of the loading chamber was closed, power was made on, and adjustments were made on the display unit of the control chamber for specimen code, rate of loading and percentage of the limiting load to be applied after failure. The load was applied at a rate of 0.3MPa/s (ASTM C 39 recommends a loading rate of 0.15 to 0.35MPa/s). When the given percentage of load after failure was attained, the control automatically stops the test. At the end of the test, the maximum load and the corresponding stress were read on the display board of the control chamber, and also the mode of failure was noticed as shown in Table B-2.

3.4.2 Bending Test

After 28 days of curing, the beam specimens were removed from the moist storage, turned on their sides with respect to their position as cast and recessed at a span of 440mm. The supporting (bearing block) was placed at the center of the lower frame platen and the load-applying accessory was connected to the loading cell of the UTM 70-C 0820/C. Thereafter, the bearing block with the test beam was brought to the surface of the loading system in such a way that a gap of 5 to 10mm was remained between the beam specimen and the load-applying accessory.

After ensuring the exact alignment of the beam specimen in relation to the loading systems, the test was started by clicking the "PUMP", "START", and "LOAD" buttons on the PC. The rate of loading was adjusted in the control console by selecting the loading

speed options on the display unit of the PC. During testing, the load-deflection diagram was automatically appeared on the display unit by the Universal Winsoft Testing software (UWT-8) installed in the PC. At the end of testing, the test results were saved and printed. Further, the location and type of rupture were noted as shown in Table B-3.

In the load-deflection diagram, the discrepancies at the beginning of the diagram were corrected by extending the main line at the kinked part of the graph towards the deflection axis. Basically, the UTM machine reads the positive load value when there is a reactive (resistance) against the direction of loading. Thence, the negative loads at the beginning of the diagram were the result of the 5-10mm gap that was intentionally provided between the test beam and the loading accessory, and those at the end were due to the complete cracking of the beams losing their resistance. In addition, the instability of the pumping oil (jerk effect) may induce negative pressure during the change in resistance and loading rate.

4 DISCUSSIONS AND ANALYSES ON TEST RESULTS

4.1 Effects of Jute Fibre on Properties of Fresh Concrete

Table 4.1 shows some properties of the fresh concrete that were recorded during the mix and specimen preparations. The inclusion of jute fibre in the concrete creates problem of workability as dictated by the poor trowel workability and nil slump results. When a great deal of fibre is mixed with the concrete, it balls the paste and hinders the uniform grain formation and free circulation of the concrete matrix, thereby, it requires greater effort to mix, trowel, vibrate and place the concrete into the molds as compared to the unreinforced concrete. On the contrary, the concrete gets stiff when fibre is added to the mix because of the tendency of fibres to closely attach the mix components.



Plate (a) Balling problem



Plate (b) Inconvenient specimen casting



Plate (c) Nil slump

Figure 4.1 Properties of Fresh Concrete

Further, the unit weight of the fresh concrete gets decreasing as the fibre concrete increases. About 6% decrease in weight was observed at 1% by volume of fibre content. This is best explained by the presence of voids due to the inconsistency of concrete flow

trapped by the fibres during casting of the cubes. Besides, the presence of fibre reduces the consumption of aggregates in the mix preparation resulting in lesser weight in view of the fact that the weight of fibre is less than that of the aggregates.

Table 4.1 Properties of Fresh JFRC

| Characteristics of fresh concrete | Fibre content by volume (%) | | | |
|-----------------------------------|-----------------------------|---------|---------|---------|
| | 0.00 | 0.25 | 0.50 | 1.00 |
| Cohesiveness | Low | Normal | High | High |
| Troweling workability | Good | Fair | Poor | Poor |
| Slump test (mm) | 23.00 | 4.00 | 0.00 | 0.00 |
| Unit weight (kg/m ³) | 2374.16 | 2351.04 | 2319.14 | 2231.66 |

4.2 Effects of Jute Fibre on Mechanical Properties of Concrete

4.2.1 Compressive Strength

Table 4.2 shows the test results of 28-days compressive strength for different fibre contents. The compression test results for the control group is slightly less than the expected strength. This might be attributed to the following factors:

- The sand and gravel utilized for the test were damp in the laboratory months before the test. Although the aggregates were thoroughly washed, the gravel was observed to be easily disintegrated during the sieve operation. In addition, the sand seems to be coarser as dictated by the fineness modulus. Hence, these factors might contribute to the reduction in strength.
- The storage of cement utilized has not been clearly known and that might cause a prolonged hydration process.
- Further, technical errors in the laboratory activities such as mixing and testing might cause the discrepancies.

From the result it can be seen that the presence of high fibre content reduces the compressive strength of concrete. This agrees with the result reported by G. Shimizu et al

[13]. However, at lower fibre content (0.25%) there is an increase in compressive strength on account of the lesser voids as compared with the higher fibre content and confining effect of the fibre prevents early tensile crack propagation. At higher fibre content there are more voids in the concrete due to the lack of free rearrangement of the concrete matrix as a result of the poor workability and balling effect during vibration and casting of the specimens.

According to the distortion energy failure theory (Huber-Van Mises-Hencky theory), failure is predicted to occur in the multi-axial state of stress when the distortion energy per unit volume becomes equal to or exceeds the distortion energy per unit volume at the time of failure in a simple uniaxial stress testing using a specimen of the same materials. The distortion energy per unit volume is the difference between the strain energy associated with volume change and the total strain energy per unit volume [35]. This theory verifies the increment in compressive strength at lower fibre content. At lower fibre content, the jute fibre closely binds the JFRC constituent, results an intact composite and this requires more energy to distort the specimen up to failure. Although the jute fibre imparts the same effect to the composite at higher fibre content, the presence of significant air voids weakens the specimen and it will be easy to distort with minimal energy.

Table 4.2 Average Compressive Strength of JFRC at 28-Days

| Test series | Average strength (MPa) | Standard deviation | Variation from the control (%) |
|--------------------|-----------------------------------|---------------------------|---|
| 1 | 17.40 | 0.48 | - |
| 2 | 18.10 | 0.59 | 4 |
| 3 | 16.01 | 0.33 | -8 |
| 4 | 16.68 | 0.43 | -4 |

Although there seems to be a tendency of fibres to decrease the compressive strength of concrete, there is an improvement of yield plateau after cracking of concrete occurred. The presence of fibres interferes with the sudden explosion of concrete matrix ingredients

during failure thereby reduces the rate of rapid failure as shown in the Figure 4.2 below and this results in improved energy absorption capacity as reported by P. Jorillo Jr et al [10]. The crack propagates rapidly in the weakest failure zone for the control specimens as shown in plate (a) of Figure 4.2. On the other hand, there is multidirectional flow of cracks for the JFRC specimens (see Figure 4.2 of plate (b), (c) and (d)). This is possible through stress transfer across the cracks and the fibre arrests the rapid crack propagation and prolongs the strain life to continue beyond the ultimate.

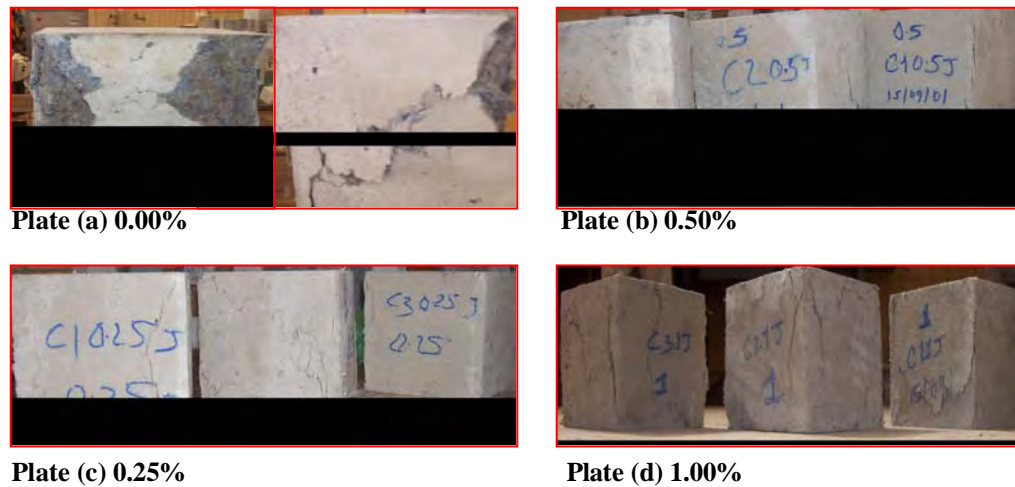


Figure 4.2 Compression Test Failures for Different Jute Fibre Content

The reduction in the sudden explosion of concrete during failure can be supported by the stress-strain diagram of Coir FRC developed by P. Jorillo Jr et al [10] as shown in Figure 4.3. While the stress-strain diagram for plain concrete (0.00% fibre) shows sudden fall beyond the ultimate, the diagrams for FRC (0.50%, 1.50 and 2.5%) show gradual declining of strain capacity after failure.

Although the test equipment employed in this thesis does not have the mechanism to record the stress-strain data for JFRC, similar failure patterns were observed as shown in Figure 4.2.

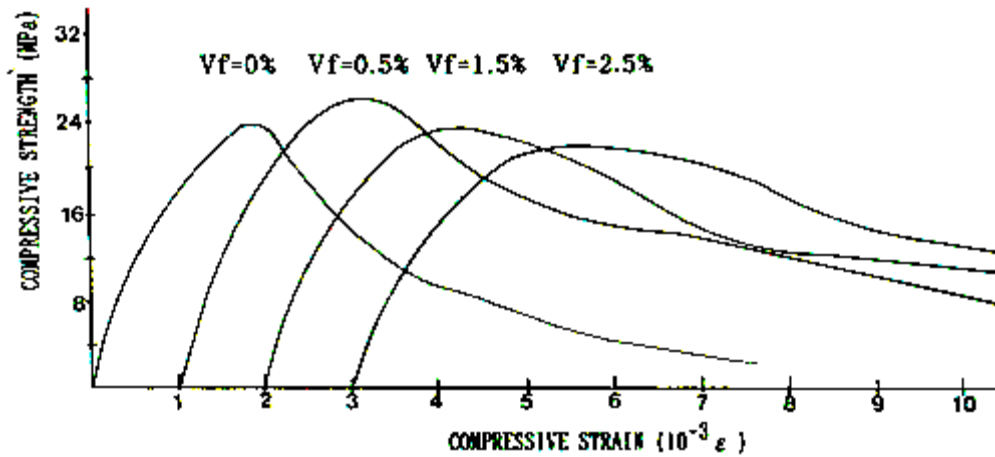


Figure 4.3 Typical Stress-Strain Diagrams for Coir FRC [10]

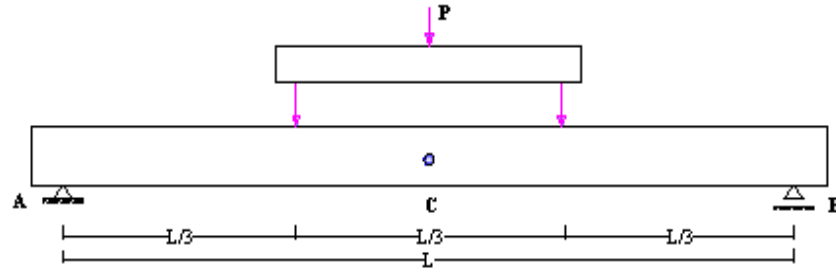
4.2.2 Flexural Strength

Table B-3 presents the bending test results at 28-days. During the test it was observed that all beams failed by rupture (flexure) and all the failures occurred in the middle third span of the test beams. Therefore, equation (2.2) was used to calculate the modulus of rupture and the results are shown in Table 4.3 below.

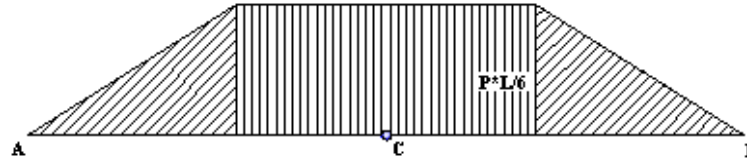
Table 4.3 Average Failure Load and Modulus of Rupture of JFRC at 28-Days

| Test series | Average failure load (kN) | Standard deviation | Modulus of rupture (MPa) | Variation from control (%) |
|-------------|------------------------------|-----------------------|-----------------------------|-------------------------------|
| 1 | 4.75 | 0.07 | 2.09 | - |
| 2 | 6.13 | 0.26 | 2.70 | 29 |
| 3 | 7.20 | 0.42 | 3.17 | 52 |
| 4 | 6.07 | 0.67 | 2.67 | 28 |

For the purpose of checking the test results, the theoretical cracking load is estimated based on the average flexural strength corresponding to the control specimens. The statical system that simulates the laboratory set up is shown in Figure 4.4.



(a) Statical system



(b) Bending moment diagram (BMD)

Figure 4.4 Statical Systems and Bending Moment Diagram

The theoretical cracking moment, M_{cr} is calculated using equation (4.1) [33].

$$M_{cr} = 1.7 * f_{ctk} * Z \quad (4.1)$$

Moreover; $Z = \frac{I_g}{c_b} = 0.17 * 10^6 \text{ mm}^3$ and $f_{ck} = 17.40/1.25 = 13.92 \text{ MPa}$

$$f_{ctk} = 0.21 * (f_{ck})^{2/3} = 1.22 \text{ MPa} \quad [33]$$

Substituting the values in equation (4.1), we get $M_{cr} = 0.35 \text{ kN} - \text{m}$.

The load pertaining to the cracking moment can be determined by equating the bending moment at the mid-span to be equal to M_{cr} .

Thus, $M_{cr} = P * L / 6 \Rightarrow P = M_{cr} * 6 / L = 4.77 \text{ kN}$.

The corresponding load obtained from the test result is 4.75kN. The theoretical value is greater than the experimental result which is to be expected. This is due to the fact that the mean strength was used in the calculation. It was not convenient to determine the characteristic strength (few samples were tested i.e. 3 specimens).



Plate (a) Failure at 0.00% Jute fibre



Plate (b) Failure at 1.00% Jute fibre



Plate (c) More voids at 1.00% Jute fibre

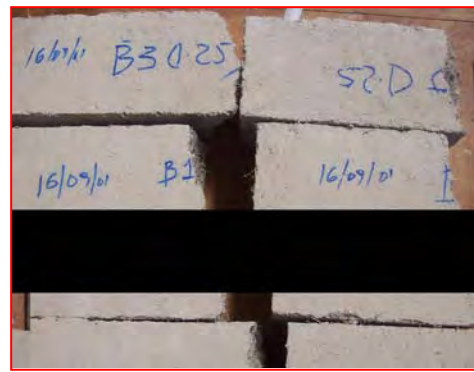


Plate (d) Intact specimen at 0.25% Jute fibre

Figure 4.5 Bending Test Failures

The bending test results shown in Table 4.3 indicate that there is significant improvement of flexural strength due to the addition of jute fibre as dictated by the increase in modulus of rupture. There is as much as 50% increment in modulus of rupture at 0.50% jute fibre content. The trend of flexural strength varies directly with the jute fibre content up to certain amount, beyond which it tends to decrease. As the fibre content increases, the balling of JFRC during mixing creates many voids in the specimen which in turn forms prior weak zones as shown in plate (c) of Figure 4.5. When failure is initiated for such beam specimen, cracks would proceed along the pre-weak zones with lesser cracking load as compared with the intact specimen at lower fibre content.

Generally, the presence of fibre diverts the crack path in search for the weak zone through tensile stress transfer across the cracks and in the meantime there will be a delay in collapse of the beam providing a relatively ductile failure.

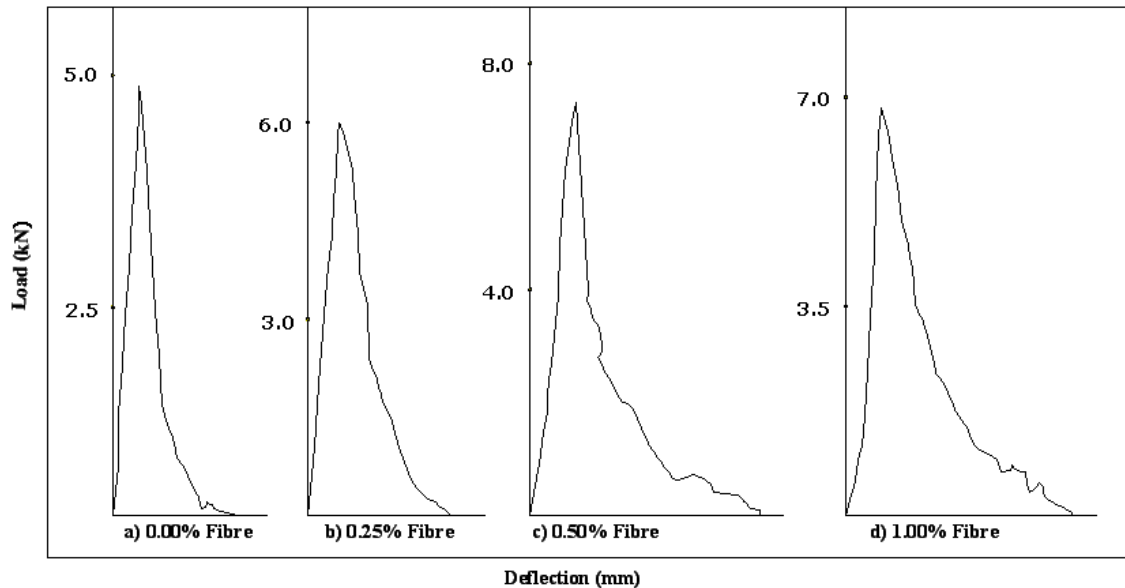


Figure 4.6 Typical Flexural Load-Deflection Curves for JFRC

Figure 4.6 shows typical bending test load-deflection diagrams of JFRC. The result reveals that the load-deflection diagram for the plain concrete has a lower failure load and very steep curves after failure. On the contrary, the load-deflection diagram after failure for higher fibre content (1%) has got a mild slope indicating that JFRC acquires a better ductility and toughness behavior as compared with the unreinforced concrete.

According to K. Schrader [19], the first crack load of FRC depends on the amount, length configuration, strength and ductility of fibres apart from other factors such as cement content and aggregates. As can be visualized in Figure 4.7, the ultimate load and first crack load for low strength and brittle fibres are close to one another whereas there is much difference for high strength and ductile fibres. Since the jute fibre is more brittle as compared with the steel fibres, most of the experimental results signify that the ultimate and first crack loads are nearly equal. The contribution of the jute fibre is rather observed on the ability of JFRC composite to maintain the ultimate load through further deflection without sudden collapse.

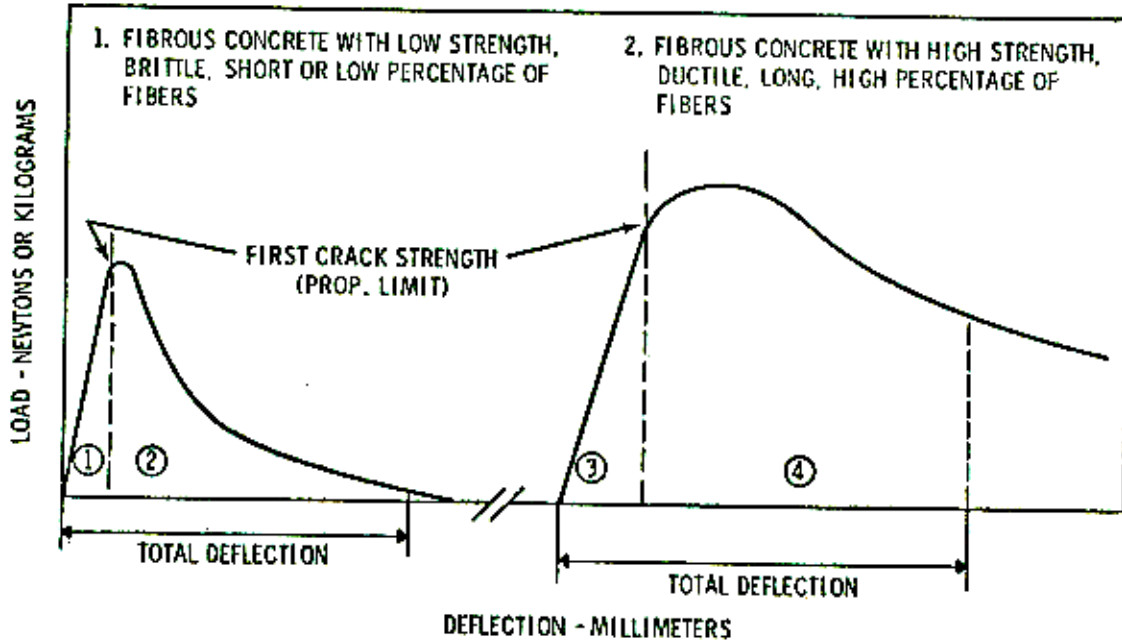


Figure 4.7 Typical Load-Deflection Curves for FRC [19]

Table 4.4 shows the mid-span deflection at the first crack load obtained from experimental results and from theoretical results. The theoretical deflections were calculated using equation (2.1) for the corresponding first-crack load read from the load-deflection diagrams shown in Annex 1. The discrepancies at the beginning of the load-deflection diagrams for some graphs with initial kinks were corrected by extending the straight part of the graph at the kinked point towards the deflection axis.

In the first crack deflection calculations, the modulus of elasticity of reinforced composites was estimated using the law of mixture as formulated in equation (4.2) [3]. The E_f used in the calculation was $75GPa$ [5, 6].

$$E_{co} = E_f * V_f + E_m * V_m \quad (4.2)$$

$$E_m = 9.5 * (f_{ckm} + 8)^{1/3} = 27.00GPa \quad \text{and} \quad \nu = 0.10 [33]$$

Moreover, $L = 440mm$, $d = 100mm$, $I = 8.33 * 10^6 mm^3$.

Table 4.4 Average First-Crack Deflection of JFRC

| Test series | E_c (GPa) | P (kN) | δ_{cr} , Recorded (mm) | δ_{cr} , Computed (mm) | Deviation (%) |
|-------------|----------------|-------------|----------------------------------|----------------------------------|------------------|
| 1 | 27.00 | 4.75 | 0.0393 | 0.0353 | 11 |
| 2 | 27.12 | 6.13 | 0.0618 | 0.0454 | 36 |
| 3 | 27.24 | 6.85 | 0.0443 | 0.0505 | -12 |
| 4 | 27.47 | 5.93 | 0.0235 | 0.0434 | -45 |

There is an average deviation of 25% between the theoretical and experimental deflections. This might be attributed to the sudden motion of the displacement encoder cable due to the jerking effect of the control console while oil pumping took place and also it was difficult to exactly locate the first crack deflection on the graphs.

The mathematical correlation between the flexural strength and the fibre parameters has been studied [10, 11]. The fact that the data results in this experimental work were not sufficient to carry out the multiple regression, few supplementary data have been imported from the results of coir FRC reported by P. Jorillo et al [10]. Thus, the mathematical correlation between the fibre parameter ($v_f * (l/d)$), modulus of rupture of the JFRC composite (f_{rco}) and that of the concrete matrix (f_{rm}) was carried on the basis of data obtained from the experimental results adjoined with the data of coir FRC.

Looking in to the trend diagrams as shown in Figure 4.8, one can clearly verify that the flexural strength of the JFRC is proportional to the fibre volume fraction up to a certain limit beyond which there will be a tendency of decay in strength. Through multiple regression analysis of the data, the prediction equation of flexural strength of JFRC was developed as shown in Equation (4.3).

$$f_{rco} = 0.50142 * f_{rm} + 0.00416 * v_f * \left(\frac{l}{d}\right) + 1.16975 \quad (4.3)$$

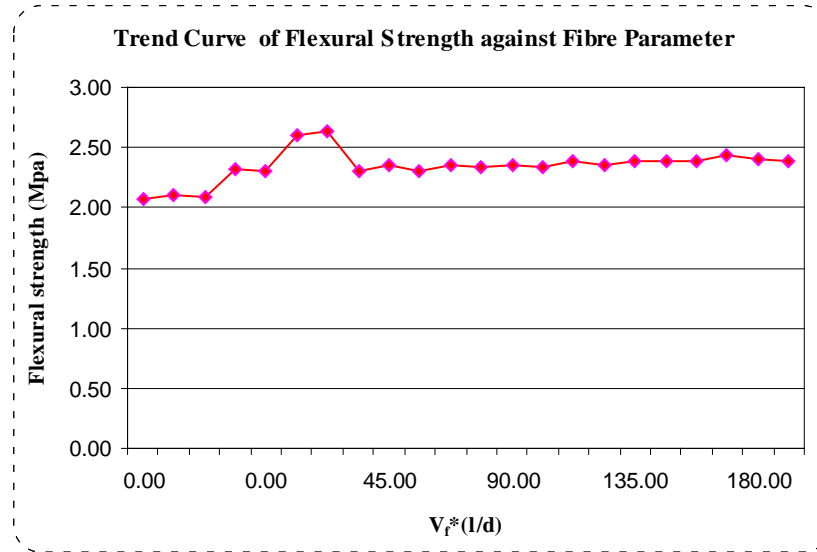


Figure 4.8 Trend Curve of Flexural Strength against Fibre Parameters of JFRC

Table 4.5 depicts the comparison of flexural strength of the experimental results with that of the prediction equation. As can be visualized in the table, there is an average difference of 10% between the strength values obtained from the prediction equation and experimental results which may be attributed to lack of sufficient data pertaining to the different fibre parameters-only single fibre aspect ratio has been considered in the laboratory. However, the values based on the prediction equation and the correlation equation reported by Al Feel et al [11] provides similar results. Despite the 10% deviation, the correlation analysis given by equation (4.3) can be used as a first hand approximation to establish the trend of flexural strength with respect to jute fibre content.

Table 4.5 Comparison of Flexural Strength of Experimental Results with that of Prediction Equation

| Fibre parameter ($v_f^*(l/d)$) | Modulus of Rupture (MPa) | | |
|----------------------------------|---------------------------------|----------------------|----------------------------------|
| | Analytical using equation (4.3) | Experimental results | Analytical by Al Feel et al [11] |
| 0.00 | 2.22 | 2.09 | 2.24 |
| 45 | 2.40 | 2.70 | 2.43 |
| 90 | 2.59 | 3.17 | 2.63 |
| 180 | 2.97 | 2.67 | 3.02 |

4.2.3 Toughness Behavior

Toughness behavior of concrete is also another parameter that plays a vital role in the design of structures. The ability of preserving strains beyond the first crack is associated with the energy required to bring complete collapse of structural members. When a structural member acquires more energy absorption capacity, then there will be a chance of cracking strains to be prolonged before complete failure. The energy absorption capacity of the JFRC has been studied by the toughness indices and residual strength factors as discussed in section 2.4.3 of this study. The toughness indices were calculated using equation (4.4) following ASTM C 1018 recommendations [29].

$$\begin{aligned} I_5 &= \frac{\text{Area under Load - Deflection Diagram up to } 3*\delta_{cr}}{\text{Area under Load - Deflection Diagram up to } \delta_{cr}} \\ I_{10} &= \frac{\text{Area under Load - Deflection Diagram up to } 5.5*\delta_{cr}}{\text{Area under Load - Deflection Diagram up to } \delta_{cr}} \\ I_{20} &= \frac{\text{Area under Load - Deflection Diagram up to } 10.5*\delta_{cr}}{\text{Area under Load - Deflection Diagram up to } \delta_{cr}} \end{aligned} \quad (4.4)$$

Similarly, the residual strength factors were also estimated as the ratio of the toughness indices [29].

$$\begin{aligned} R_{5,10} &= 20*(I_{10} - I_5) \\ R_{10,20} &= 10*(I_{20} - I_{10}) \end{aligned} \quad (4.5)$$

Table 4.6 depicts the toughness indices and residual strength factors calculated based on the bending test results of the JFRC with different jute fibre contents. ASTM C 1018 specifies that the toughness indices of plain concrete is 1.00 for all cases of I_5 , I_{10} and I_{20} . For that of the FRC the observed range of index values are 1.00 to 6.00, 1.00 to 12.00 and 1.00 to 25.00 corresponding to I_5 , I_{10} and I_{20} , respectively. The index results obtained in this work for the JFRC satisfy the code recommendations despite slight deviations which might arise from the difficulties in the determination of the first crack points and in the calculations of the area under the load-deflection curves.

Table 4.6 Toughness Indices and Residual Strength Factors of JFRC

| Test series | I_5 | I_{10} | I_{20} | $R_{5,10}$ | $R_{5,10}$ |
|-------------|-------|----------|----------|------------|------------|
| 1 | 1.01 | 1.02 | 1.02 | 0.18 | 0.00 |
| 2 | 1.01 | 1.45 | 1.55 | 8.92 | 0.95 |
| 3 | 1.17 | 1.48 | 1.58 | 6.22 | 1.05 |
| 4 | 1.30 | 1.86 | 2.09 | 11.26 | 2.31 |

From Table 4.6, one can see that the toughness indices and residual strength factors increase as the fibre content increases. There is as much as 28%, 82% and 105% increment in I_5 , I_{10} , and I_{20} respectively at 1.00% jute fibre. Similar results have been reported by several researchers [10, 13]. This result asserts that the incorporation of jute fibre in the concrete matrix significantly improves the toughness behavior of concrete. The improvement in toughness behavior allows the JFRC to absorb sufficient amount of energy. Thus, structural members made up of JFRC will have enough time to sustain the ultimate capacity before complete collapse.

4.3 Design Considerations and Areas of Applications

The initial stage of design considerations in structural engineering involves the determination of the stress-strain diagram of the particular materials utilized to construct a structure. The limitation of this thesis work lies on the inability of plotting the stress-strain diagram of the JFRC composite. This was because of the constraints in obtaining the equipment for measuring the stress-strain data during the compression test. However, the stress-strain diagram of other natural fibre reinforced composites such as coir FRC developed by P. Jorillo Jr et al [10] as shown in Figure 4.3 above, could be applied in the stress analysis of JFRC.

In the design of structures subjected to pure compression force, we can use the usual design procedures established by the relevant codes of standards for conventional concrete. For such cases the effect of fibre on the composite material can be taken into account by applying a reduction factor for the presence of voids [9].

In the design of flexural members, the contribution of fibre to the tensile capacity of the section shall be incorporated in the stress-strain diagram of the FRC composite sections. Two major cases could be considered in this regard: structural members constructed from only FRC composite and those provided with additional steel reinforcement.

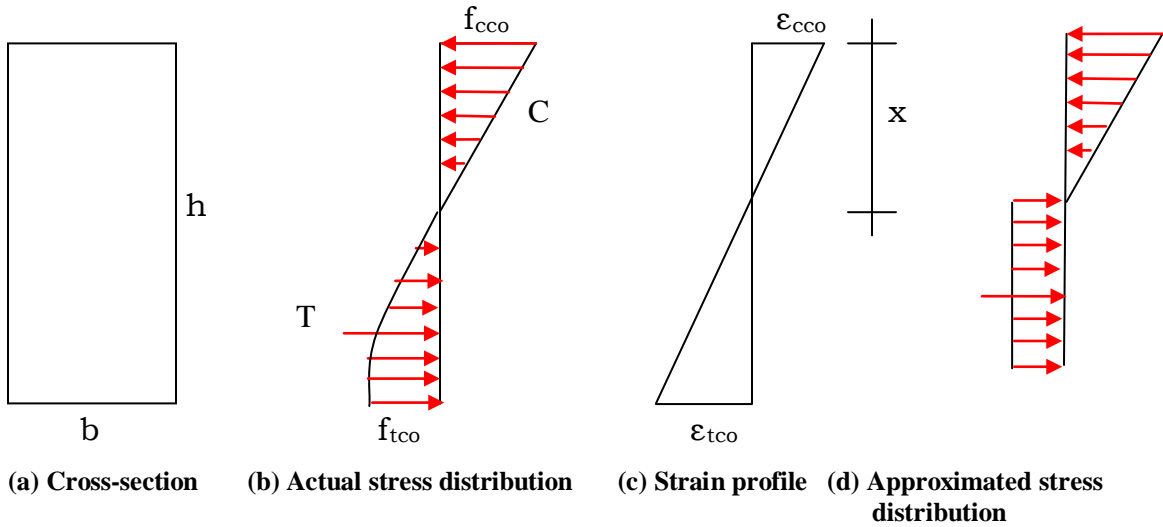


Figure 4.9 Stress Analysis of FRC in Bending without Additional Steel Reinforcement

When flexural members composed of only FRC are subjected to bending actions up to failure, the extreme fibre stress of the compression zone is far less than the ultimate compression capacity of the section. Hence, the stress distribution of the compression zone can be assumed to vary linearly across the depth of the section. The actual stress distribution in the tension zone is of parabolic type. However, failure of plain FRC beams is initiated in the tension zone at lower load level and the ordinate of the maximum tensile stress is not significantly far from the neighborhoods. Hence, the stress distribution in the tension zone can be reasonably assumed simple rectangular [20].

In stress analysis of members in bending, two governing conditions are essential. The first is the conditions of equilibrium of internal forces across the section shall be satisfied simultaneously (both moment and forces about and along the neutral axis, respectively). The second condition is the relationship between the extreme fibre strains (depth of compression and tension zones). The basic assumptions to be made in the stress analysis of FRC are [10, 20, 33]:

- Plane sections before bending remain plane after bending
- There is strong interfacial bond between the fibre and the matrix of the FRC composite

Consider the stress and strain diagrams of Figure 4.9.

$$C = \frac{1}{2} * f_{cco} * b * x \quad (4.6)$$

$$T = f_{tco} * b * (h - x) \quad (4.7)$$

Applying the normal force equilibrium along the neutral axis yields:

$$C = T \quad (4.8)$$

Substituting equations (4.6) and (4.7) in equation (4.8), we get:

$$f_{tco} * b * (h - x) = \frac{1}{2} * f_{cco} * b * x \quad (4.9)$$

Let k_x denotes the related neutral axis depth.

$$\text{Thus, } k_x = \frac{x}{h}.$$

Multiplying both sides of equation (4.9) by $\frac{1}{h * b}$ and re-arranging in terms of k_x , we get:

$$f_{tco} * (1 - k_x) = \frac{1}{2} * f_{cco} * k_x \quad (4.10)$$

Similarly, taking the moment of forces about the point of application of the resultant compression force yields:

$$M = f_{tco} * b * (h - x) * \left(\frac{h - x}{2} + \frac{2}{3} * x \right)$$

Multiplying the right side of the moment equation by a factor of $\frac{h^2}{h^2}$ and rearranging using k_x , results the moment expression.

$$M = f_{tco} * b * h^2 * (1 - k_x) * \left(\frac{1}{2} + \frac{k_x}{6}\right) \quad (4.11)$$

Compressive strain in the extreme fibre of the compression zone can be determined using similarity of triangle in the strain profile.

$$\varepsilon_{cco} = \frac{x}{h - x} * \varepsilon_{tco} \quad (4.12)$$

Stress-strain relation:

$$\varepsilon_{cco} = \frac{f_{cco}}{E_{co}} \quad (4.13)$$

Comparing equations (4.12) and (4.13):

$$f_{cco} = \frac{x}{h - x} * \varepsilon_{tco} * E_{co} \quad (4.14)$$

Multiplying both sides of equation (4.14) by $\frac{h}{h}$ and rearranging in terms of k_x , we get:

$$f_{cco} = \frac{k_x}{1 - k_x} * \varepsilon_{tco} * E_{co} \quad (4.15)$$

Substituting equation (4.10) in equation (4.15) and simplifying, results the following expression:

$$k_x^2 + 4 * \frac{f_{tco}}{\varepsilon_{tco} * E_{co} - 2 * f_{tco}} * k_x + 2 * \frac{f_{tco}}{2 * f_{tco} - \varepsilon_{tco} * E_{co}} = 0 \quad (4.16)$$

$$\text{Let, } \alpha = 4 * \frac{f_{tco}}{\varepsilon_{tco} * E_{co} - 2 * f_{tco}} \quad (4.17)$$

Thus, equation (4.16) becomes:

$$k_x^2 + \alpha * k_x - \frac{\alpha}{2} = 0 \quad (4.18)$$

Solving for k_x and taking the positive value, we get:

$$k_x = \frac{-\alpha + \sqrt{\alpha^2 + 2 * \alpha}}{2} \quad (4.19)$$

Therefore, for a given limit of tensile strain of a particular FRC, one can evaluate the corresponding stress and strain using equations (4.12), (4.15), (4.17), (4.19) and the moment, M using (4.11).

For verification, consider the control specimen test results. $f_{tco} = 1.22 MPa$. The corresponding limiting tensile strain, ϵ_{tco} is read from the tensile stress-strain diagram of polymer FRC [20], just for approximation (since no such diagram is developed in this study). Hence, $\epsilon_{tco} = 0.15 * 10^{-3}$. Substituting these values in equations (4.17), (4.19) and (4.11), we get $M = 0.39 kN - m$. From the test result, $P = 4.75 kN$ and the corresponding moment is, $M = \frac{P * L}{6} = 0.35 kN - m$. There is 11% deviation between the computed and test results which might be due to the lack of exact determination of the limiting tensile strain. Note that this is not an exhaustive work on the design aspects of JFRC and hence the exact stress distribution of the JFRC composite has to be developed using experimental results.

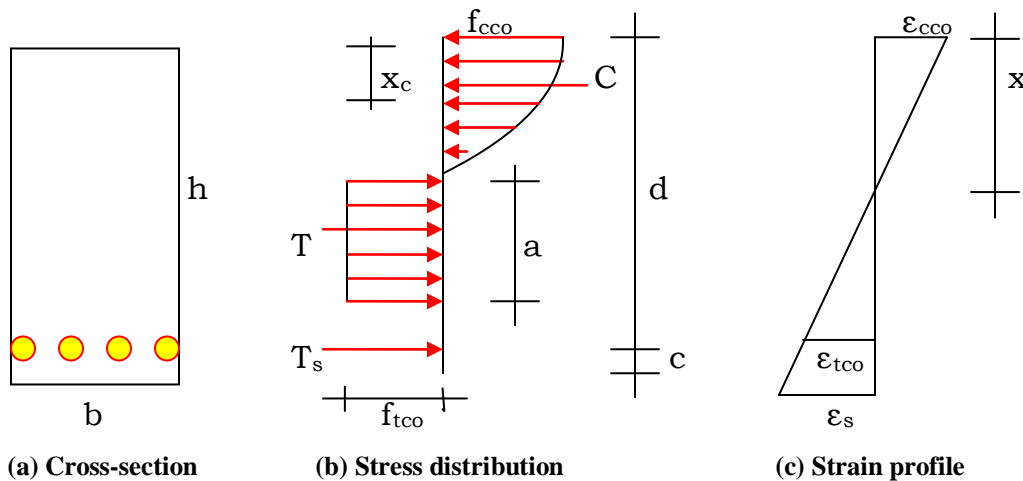


Figure 4.10 Stress Analysis of FRC in Bending with Additional Steel reinforcement

In the case of beams made of FRC but with additional steel reinforcement, the stress level in the compression zone could be fully exhausted, depending on the percentage of the steel reinforcement. In such scenario, the stress distribution assumed by A.M Ivanov as shown in Figure 4.10 can be utilized in the stress analysis. Thus, the stress distribution in the compression zone can be assumed to be parabolic and that of the tension zone to be rectangular-the depth of which depends on the type of FRC and steel grade. When the FRC beam is provided with additional steel reinforcement, the tensile stress in the tension zone is shared between the FRC and the steel reinforcement. When a higher percentage of steel is provided, most of the tensile stress is taken up by the steel reinforcement and the fibres may not be significant. Thus, to account for this phenomenon, the depth of the tension zone is reduced in relation to the percentage of steel reinforcement.

Following the above calculation procedures and adopting the stress and strain diagrams depicted in Figure 4.10, one can develop analogous expressions for the different design parameters.

Similarly, the moment-curvature relationships of FRC can be established using the stress and strain distributions presented so far. The curvature (ρ) of a flexural member is represented by the gradient of strain profile at the element. Basically, the curvature of a given FRC section (such as Figure 4.8) is given by equation (4.20) [34].

$$\rho = \frac{\varepsilon_{cco}}{k_x} = \frac{\varepsilon_s}{h*(1-k_x)} = \frac{\varepsilon_{cco} + \varepsilon_{sco}}{h} \quad (4.20)$$

Hence, the moment curvature relationship for a given FRC section can be determined by assuming intervals of extreme fibre strain (ε_{cco}) of the compression zone. For each value of ε_{cco} , the related neutral axis depth (k_x) satisfying equilibrium is calculated by adjusting k_x until the internal forces determined using equations (4.6) and (4.7) balance the corresponding external action effects. Then, the internal forces and neutral axis depth determined so far can be utilized to calculate the moment and curvature from equations (4.11) and (4.20) respectively. Finally, the moment-curvature diagram can be plotted using these values.

The significance of the JFRC in view of moment curvature is clearly visible. Although the change in cracking strength of JFRC may not be significant, the ability of jute fibre to sustain the ultimate strain in the tensile zone to a remarkable limit provides ductile behavior as depicted in the load-deflection diagrams on Figure 4.6. When such a section is subjected to bending up to failure, the presence of jute fibre allows the composite section to enter in to some degree of plastic zones. This phenomenon would permit the curvature of the section to increase more than the concrete matrix does.

As a general remark, the design of structures made of FRC encompasses:

- Determination of the geometric parameters of the structural member
- Carry out analysis of the structure acted up on by external actions
- Determination of strength of FRC composite that suit the stress analysis results-using the design philosophies stipulated by the relevant codes of standards. At this stage, determination of the fibre content of the composite and the steel reinforcement ratio are also part of the design processes.
- Determine the moment-curvature relationships of the FRC section (if required) based on the final design provisions.

As the scope of the thesis work is limited, comprehensive design consideration is not presented. However, analysis and design of FRC is available in literatures [10, 19, 20].

Despite the appreciable usage of natural fibres in concrete composite constructions, there are problems experienced with the poor durability of natural fibres in reinforced cement composites probably due to alkali attack of the fibres by the pore water present in the cement matrix and by the exposure conditions such as temperature and pressure [16-18]. The presence of the OH^- ion oxidizes the cellulose and also at higher temperatures, around 75°C , the degree of polymerization of cellulose will be damaged and the lignin portion begins to soften losing its binding property. In addition, the lignin has no resistance to alkaline medium [17]. P. Soproushian et al [18] demonstrated that the precipitation of cement hydration within cellulose fibre cores and at interface zones is the

key deterioration mechanism. Further, it was observed that the fibre-to-matrix bond is adversely affected by moisture effects.

With passage of time under normal conditions, FRC manufactured from natural and plastic fibers would lose some of its positive characteristics as a result of age effects, which depends considerably on exposure to solar or ultraviolet rays and on the impact of heat. Therefore, the use of natural fibre-reinforced concrete in exposed forms of construction has to be checked for age effects [20].

Several fibre treatment methods have been explored so far, the choice of which depends on cost, easy way of processing and effects on the fibre structure. Some of these are: surface washing to remove soluble substances at fibre surface as well as the residues and dusts, changing the alkalinity of the pore water, replacing part of the cement with silica fume and reduce moisture sensitivity using natural pozzolanas such as rice husk ash and bagasse ash in the mix or by sealing the pore system using additives in the mix or impregnating with chemicals [17, 18].

The question of durability of natural fibre-reinforced concrete shall not be a discouraging phenomenon in the FRC technology. Instead, technical justifications are essential in the applications of FRC: either well developed protection methods have to be looked into along with the objective of economy or search for situations where fibre durability is a minimal. Structures with light-weight mine props, lining of mine shafts, impermeable constructions with short life span, concrete masonry blocks and temporary structures are some of those areas in which only short term strength is required, thus natural and synthetic fibres may be used to reinforce the corresponding matrix [20].

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Difficulties attributed to low efficiency in tensile strength of structural elements, brittle mode of failure, rapid crack propagation and increased overload are common in the concrete construction industry. Whereas ordinary steel reinforced concrete is the most popular mechanisms developed so far to alleviate such problems, it is rather becoming expensive in production costs, transportation of pre-cast members, maintenance costs and the supply of much amount of steel, which takes huge capital investment to produce locally. These impediments have driven the development of contemporary concrete technologies such as high strength concrete, fibre reinforced concrete (FRC), shotcrete etc, in which all the advancements entail an investigation into the constitutive materials.

This thesis is part of such works dealing with the experimental assessment of flexural and compressive strengths of JFRC with different jute fibre contents. The study was carried out by conducting compression tests on cube specimens and two point bending test on beam specimens at different jute fibre content. From the results and analysis of the thesis work it can be concluded that:

- (1) The incorporation of jute fibre as a constitutive material of concrete affects the rheological properties of the fresh concrete. High fibre content in the concrete matrix reduces workability and unit weight.
- (2) Reduction in the compressive strength of concrete has been observed at higher fibre content. Despite the reduction in the compressive strength of JFRC, there is an improvement of ductility after cracking of concrete through stress transfer across the cracks and the fibre arrests the rapid crack propagation and prolongs the strain life to continue beyond the ultimate.
- (3) The incorporation of jute fibre increases the modulus of rupture of concrete by 50% at 0.50% jute fibre content.

- (4) The multiple regression curve developed in equation (4.3) can be used as first hand approximation to establish the trend of flexural strength with respect to jute fibre content.
- (5) Jute fibre significantly improves the toughness behavior of concrete. There is as much as 28%, 82% and 105% increment in I_5 , I_{10} , and I_{20} respectively at 1.00% jute fibre. The improvement in toughness behavior allows the JFRC to absorb sufficient amount of energy before complete collapse.
- (6) The test results have shown that fibre content in the JFRC composite is an essential parameter that influences both the rheological and mechanical properties of concrete. Therefore, it is worth noting that fibre content along with other composite parameters has to be closely viewed in the study of JFRC.

5.2 RECOMMENDATIONS

Based on the insights gained from the test results and analyses of the JFRC, the incorporation of jute fibre in making FRC composite would be one of the promising strategies to improve the performance of concrete. The greater improvement in flexural and toughness behavior of JFRC outshine the minimal reduction of compressive strength at higher fibre content. The significant improvement in toughness behavior allows the JFRC to absorb sufficient amount of energy and hence, structural members made up of JFRC will have enough time to sustain the ultimate capacity before complete collapse.

In spite of the limited scope of the thesis work, the problem of durability of jute fibre at sever exposure conditions and degradation of JFRC by aging; the investigation results would indicate the possibility of utilizing JFRC in various applications. To this end, the thesis work results elite a hope that JFRC can be used in areas where small tensile reinforcement is expected, such as ground floor slabs, framing of small scale structures like villas etc. Further, JFRC can be employed in the construction of temporary structures including detours and refuge camps. The least cost of jute fibre, its being renewable resources, the reduced weight of the JFRC composite and the reduction in consumption

of other constituents of the concrete matrix would clearly show the economic advantage of JFRC.

While an assessment of Flexural and Compression Strengths of JFRC and a method of producing same and modifications thereof have been shown and described in detail in this thesis, various additional changes and modifications may be made without departing from the scope of the present study. The length of jute fibre used in the thesis was based on the optimum aspect ratio speculated from the results of Coir FRC by G. Shimizu et al [13], hence the optimum aspect ratio of the jute fibre has to be determined in further works. In addition, the design concepts discussed herein are not exhaustively articulated, thus detail investigations of stress-strain behavior of JFRC composite has to be made in the future.

The study of Flexural and Compressive strengths of other Fibre-Reinforced Concrete may also be carried out in association with the methods and techniques outlined in this study for JFRC. Likewise, scholars may continue to study jute fibre-reinforced concrete by including other parameters such as Fatigue, Shear Capacity, Ductility, etc apart from the flexural and compressive strength parameters.

APPENDIX

APPENDIX-A LABORATORY PROCEDURES AND CHECKLISTS

This section describes the standard procedures and checklist utilized in accomplishing different laboratory activities. The total scheme has been organized in reference to international standards and literatures [4, 19]. During the laboratory works a check mark (√) was made on the mark column of the check list after accomplishing the required activities. This was basically intended to ensure appropriate accomplishment of every item of activities for as particular test.

Table A-1 Procedure and Check List for Sieve Analysis of Aggregates

| S/No | Activities | Mark | Remarks |
|------------|--|------|--------------------------------|
| 1.1 | Sieve Analysis of Sand (ASTM C 136) | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Weighing scales | √ | |
| | Trowel | √ | |
| | Shaking machine | √ | |
| | Set of sieves | √ | |
| | Measuring cylinder | √ | |
| b | Select a representative sample from the damp sand by quartering | √ | Successive quartering was done |
| c | From the representative sample select 0.007m ³ by quartering | √ | |
| d | For sieving, select about 500g from (c) | √ | |
| e | Air-dry the sample in (d) | √ | |
| f | Weigh the air-dry sample in (e) to the nearest 0.5g | √ | |
| g | Arrange the set of sieves in the order of their size | √ | |
| h | Place the nest of the arranged sieves in the shaker | √ | |
| i | Add the 500g air-dry sample on top of sieve, then cover the sieve and clamp securely | √ | |
| j | Then shake for 2,000 oscillations (for about 10 minutes) | √ | |
| k | Weigh the residue in each sieve and in the pan to 1/000 of the weight of the sample | √ | |
| l | Check the sieve operation by hand sieving, according to ASTM C 136 | √ | |

| S/No | Activities | Mark | Remarks |
|--|--|------|---|
| m | Find the sum of weights of material retained in each sieve | √ | |
| n | If the value in (m) is not equal to 500g within 1%, then repeat the sieve test | √ | The sieving conforms to the requirement |
| o | Calculate the percentage passing and retained to the nearest 1% | √ | |
| p | Calculate the fineness modulus | √ | |
| q | Plot the grading chart in standard format-ASTM C 136 | √ | |
| 1.2 Sieve Analysis of Gravel (ASTM C 136) | | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Weighing scales | √ | |
| | Balance with scoop | √ | |
| | Trowel | √ | |
| | Set of sieves | √ | |
| | Measuring cylinder | √ | |
| b | Select a representative sample from the damp gravel by quartering | √ | Successive quartering was done |
| c | From the representative sample select 0.015m ³ by quartering | √ | |
| d | For sieving, select about 7kg from (c) | √ | |
| e | Air-dry the sample in (d) | √ | |
| f | Weigh the air-dry sample in (e) to the nearest 0.5g | √ | |
| g | Screen the sample by hand successively through all the screens, using one at a time and starting with the largest. Shake on each screen until no more pass. In no case shall the fragments in the sample be turned or manipulated through the screen | √ | |
| h | Weigh the residue in each sieve and in the pan to 1/000 of the weight of the sample | √ | |
| i | Check the sieve operation by hand sieving, according to ASTM C136 | √ | |
| j | Find the sum of weights of material retained in each sieve | √ | |
| k | If the value in (m) is not equal to 500g within 1%, then repeat the sieve test | √ | |
| l | Calculate the percentage passing and retained to the nearest 1% in tabular format | √ | The test conforms to the requirement |

| S/No | Activities | Mark | Remarks |
|------|---|------|---------|
| m | Calculate the fineness modulus | √ | |
| n | Plot the grading chart in standard format | √ | |
| | | | |

Table A-2 Procedure and Check List for the Specific Gravity and Absorption Capacity of Aggregates

| S/No | Activities | Mark | Remarks |
|------------|--|------|---------|
| 2.1 | Specific Gravity and Absorption Capacity of Sand (ASTM C-128) | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Platform scale | √ | |
| | Balance with scoop | √ | |
| | 1-pt mason-jar pycnometer or 500-ml volumetric flask | √ | |
| | Conical mold top 40mm dia, bottom 90mm dia, height 75mm | √ | |
| | 25mm dia tamping rod | √ | |
| | Two 6-in pans and two 12-in pans | √ | |
| | Measuring cylinders | √ | |
| | Trowel | √ | |
| b | Select a representative sample from the damp sand by quartering | √ | |
| c | Screw the pycnometer cap and make match marks to show its position on the jar | √ | |
| d | Weigh the pycnometer empty | √ | |
| e | Weigh the pycnometer filled with water at room temperature | √ | |
| f | Gently roll and agitate the jar to eliminate air bubbles | √ | |
| g | Determine the capacity of the pycnometer from (d) and (e) | √ | |
| h | Select 1500-g of sand from (b) | √ | |
| i | Saturate the sample in (h) | √ | |
| j | Air-dry the sample (SSD), by spreading on a clean, flat surface | √ | |
| k | Check for surface dry using conical mold (ASTM C 128) | √ | |
| l | Immediately introduce 500-g of the SSD sand into the pycnometer | √ | |
| m | Fill the jar with water (90% of total capacity up to the mark) and screw down till the match mark in (c) | √ | |
| n | Gently roll and agitate the jar being inclined, to remove air bubbles, then fill 100% | √ | |
| o | Weigh the pycnometer with all its contents in (n) | √ | |
| p | Determine the total weight of water introduced in the jar from (o) and (g) | √ | |
| q | Empty the jar | √ | |

| S/No | Activities | Mark | Remarks |
|--|--|------|---------|
| r | Weigh out a second 500-g sand as soon as the first is inundated in the pycnometer | √ | |
| s | Oven-dry the sample in a suitable pan or vessel for 24-hours at 100 to 110 °C | √ | |
| t | Cool the oven-dry sample to comfortable temperature | √ | |
| u | Weigh the oven-dry sample and record as the corresponding value of ``A`` | √ | |
| v | Calculate the specific gravity and absorption capacity (ASTM C 128) | √ | |
| 2.2 Specific Gravity and Absorption Capacity of Gravel (ASTM C-127) | | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Platform scale sensitive to .5g | √ | |
| | Balance with scoop | √ | |
| | Wire basket | √ | |
| | Two 6-in pans and two 12-in pans | √ | |
| | Trowel | √ | |
| | 4.75mm sieves | √ | |
| | Measuring cylinders | √ | |
| b | Select a representative sample from the damp aggregate by quartering | √ | |
| c | Saturate the sample | √ | |
| d | Select about 3-kg of aggregate | √ | |
| e | Sieve and reject all material passing 4.75mm sieve | √ | |
| f | Surface-dry the sample by rolling in a trowel | √ | |
| g | Obtain the weight in air of the SSD sample to the nearest 0.5-g | √ | |
| h | Prepare and determine the weight in water of wire basket alone | √ | |
| i | Then, immediately place the SSD sample in the wire basket and weigh all the contents | √ | |
| j | And then determine the weight in water of the sample after correcting the weight obtained in (h) | √ | (i)-(h) |
| k | Oven-dry the sample in a suitable pan or vessel for 24-hours at 100 to 110 °C | √ | |
| l | Cool the oven-dry sample to comfortable temperature | √ | |
| m | Weigh the oven-dry sample and record as the corresponding value of | √ | |

| S/No | Activities | Mark | Remarks |
|------|--|------|---------|
| | "A" | | |
| n | Calculate the specific gravity and absorption capacity (ASTM C 127) | √ | |
| | | | |

Table A-3 Procedure and Check List for the Determination of Unit Weight of Aggregates

| S/No | Activities | Mark | Remarks |
|--|--|------|---------|
| 3.1 Unit Weight of Sand (ASTM C 29/C) | | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Platform scale | √ | |
| | Balance with scoop | √ | |
| | 16mm dia and 600mm long tamping rod | √ | |
| | 1/10-cu ft (0.0028-m ³) measuring cylinders | √ | |
| | Trowel | √ | |
| b | Select a representative sample from the damp sand by sand splitter or quartering | √ | |
| c | Weigh the 1/10-cu ft (0.0028-m ³) of standard cylinder to the nearest 0.5g | √ | |
| d | Fill the cylinder one-third full of air-dry, carefully mixed sand and level it with finger | √ | |
| e | Tamp the mass with the rounded end of the rod 25 times evenly over the surface | √ | |
| f | Fill the cylinder two-third full and tamp as in (e) | √ | |
| g | Then fill the cylinder overflowing and tamp 25 times | √ | |
| h | Strike off the surplus using the rod as a straight edge | √ | |
| i | Weigh the cylinder filled with the sand as in (h) | √ | |
| j | Calculate the volume of the cylinder by measurement and check with the standard | √ | |
| k | Compute the unit weight from (c), (i) and volume of the cylinder (ASTM C-29) | √ | |
| 3.2 Unit Weight of Gravel (ASTM C 29/C) | | | |
| a | Collect, clean and arrange the following apparatus | √ | |
| | Platform scale | √ | |
| | Balance with scoop | √ | |
| | 16mm dia and 600mm long tamping rod | √ | |
| | 1/3-cu ft (0.0093-m ³) measuring cylinders | √ | |

| S/No | Activities | Mark | Remarks |
|------|---|------|---------|
| | Trowel | √ | |
| b | Select a representative sample from the damp gravel by quartering | √ | |
| c | Weigh the 1/3-cu ft (0.0093-m ³) of standard cylinder to the nearest 0.5g | √ | |
| d | Fill the cylinder one-third full of air-dry, carefully mixed sand, level it with finger | √ | |
| e | Tamp the mass with the rounded end of the rod 25 times evenly over the surface | √ | |
| f | Fill the cylinder two-third full and tamp as in (e) | √ | |
| g | Then fill the cylinder overflowing and tamp 25 times | √ | |
| h | Strike off the surplus using the rode as a straight edge | √ | |
| i | Weigh the cylinder filled with the sand as in (h) | √ | |
| j | Calculate the volume of the cylinder by measurement and check with the standard | √ | |
| k | Compute the unit weight from (c), (i) and volume of the cylinder | √ | |
| | | | |

Table A-4 Procedure and Check List for Mix Preparation of JFRC

| S/No | Activities | Mark | Remarks |
|------------|--|------|---------|
| 4.1 | Collect, Clean and Arrange the Necessary Equipment, Utensils and Apparatus | | |
| | Sampling pans | √ | |
| | Trowel | √ | |
| | Slump cone | √ | |
| | Measuring cylinder | √ | |
| | Mixer (cleaned, washed and moistened) | √ | |
| | 1,000-ml graduate | √ | |
| | 10-ml graduate | √ | |
| | 16mm dia and 600mm long tamping rod | √ | |
| | 150 by 150mm cube and 100*100*500mm beam molds | √ | |
| | Base plates | √ | |
| | Cover plates | √ | |
| | 12-in (30 mm) steel rule | √ | |
| | Chopping knives | √ | |
| | External vibrator | √ | |
| 4.2 | Material Preparation | | |
| a | Store all the materials at room temperature (20-30 ^o C) | √ | |
| b | Clean and chop the jute fibre to the required aspect ratio | √ | |
| c | Blend the coarse aggregate according to the grading requirements in the sieve analysis results | √ | |
| d | Blend the sand according to the grading requirements in the sieve analysis results | √ | |
| 4.3 | Mixing Concrete | | |
| a | Designate each mixing pan with the specific requirements | √ | |
| | Batch designation | √ | |
| | Approximate ultimate strength expected | √ | |
| | Water-cement ratio | √ | |

| S/No | Activities | Mark | Remarks |
|------|---|------|----------------------------|
| | Slump required | √ | |
| | Percentage of Jute fibre | √ | |
| b | Weigh the required amount of gravel from (c) and add to the mixer | √ | Amount as per the mix type |
| c | Weigh the required amount of sand from (d) and add to the mixer | √ | Amount as per the mix type |
| d | Weigh the required amount of cement and add to the mixer | √ | Amount as per the mix type |
| e | Add some amount of jute fibre | √ | |
| f | Do 1 minute dry mixing | √ | |
| g | Add some of the mixing water | √ | |
| h | Start the mixing and then continuously add the remaining jute fibre and water while the mixer is running for more than 3 minutes. | √ | |
| i | Cover the opened end of the mixer to prevent evaporation during the mixing period | √ | |
| j | Deposit machine mixed concrete in the clean, damp mixing pan and remix by shovel or trowel until it appears to be uniform so as to eliminate segregation, | √ | |
| | | | |

Table A-5 Procedure and Check List for the Evaluation of Properties of Fresh JFRC

| S/No | Activities | Mark | Remarks |
|------------|--|------|--------------------------------------|
| 5.1 | Cohesiveness | | |
| a | During the mixing process, note whether the concrete tends to hang together well or whether it tends to crumble readily. Rate as follows | √ | |
| | High | | |
| | Normal | | |
| | Low | | |
| 5.2 | Troweling Workability | | |
| a | Work the concrete with a trowel and rate as follows. If it appears to work smoothly and with little effort, the troweling workability may be called good. | √ | |
| | Good | | |
| | Fair | | |
| | Poor | | |
| 5.3 | Slump Test | | |
| a | The total time required to accomplish the test is 11/2 minutes | √ | |
| b | Place the slump cone (see 4.1) on a smooth and moist rigid base | √ | |
| c | Place the newly representative mixed concrete of 4.3 (j) in the mold in three layers, each approximately one-third the volume of the mold | √ | |
| d | Ensure symmetrical distribution of concrete within the mold by moving the scoopful concrete around the top edge of the mold as the concrete slides from it | √ | |
| e | Rod each layer uniformly with 25 strokes using the tamping rod specified in 4.1 above. Each stroke shall penetrate the underlying layer. Consolidation using internal vibration is not possible as the size is small | √ | |
| f | After rodding the top layer strike off the surface of the concrete with a trowel leaving the mold exactly filled | √ | |
| g | Clean the surface of the base out side the cone of any excess concrete | √ | |
| h | Immediately remove the mold from the concrete by raising it slowly in a vertical direction | √ | |
| i | If the pile topples sideways, it indicates that the materials have not been uniformly distributed in the mold and the test should be repeated. | √ | The test conforms to the requirement |

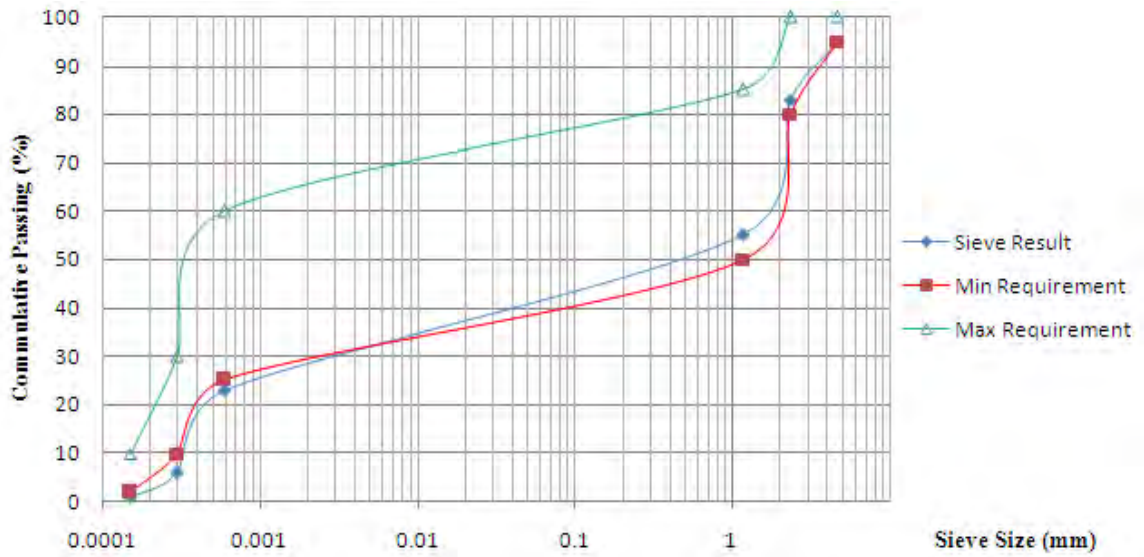
| S/No | Activities | Mark | Remarks |
|------|---|------|---------|
| j | Measure the slump immediately by determining the distance between the height of the mold and the height of the vertical axis (not the maximum height) of the specimen | √ | |
| k | Clean the mold thoroughly immediately after using | √ | |
| | | | |

Table A-6 Procedure and Check List for Test Specimen Preparation

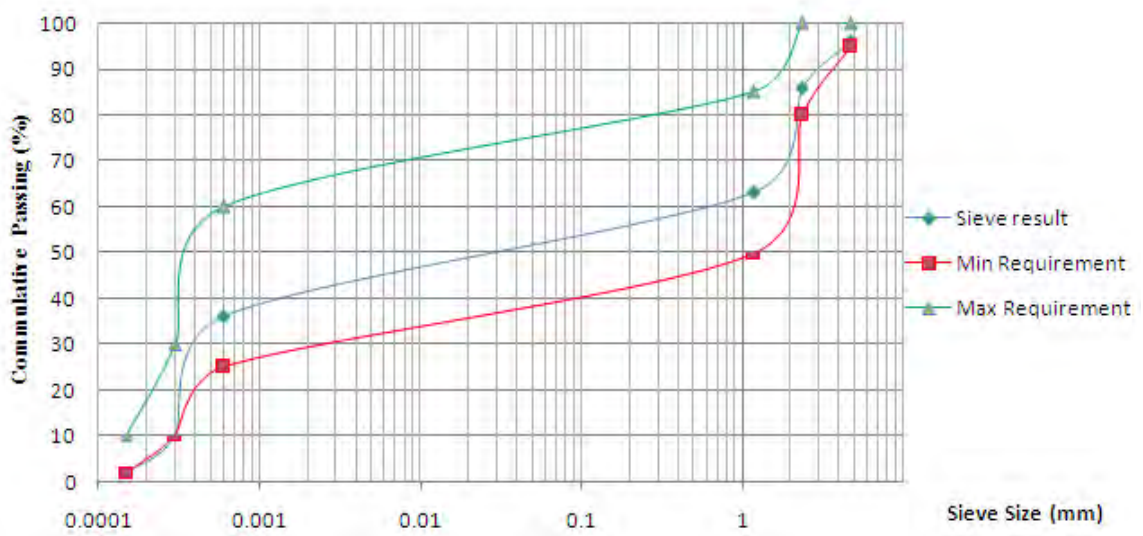
| S/No | Activities | Mark | Remarks |
|----------------------------------|---|------|---------|
| 6.1 Compression Specimens | | | |
| a | Place the molds as near as to the place where to store for 24-hours | √ | |
| b | Measure the dimensions of the molds to the nearest 0.5mm | √ | |
| c | Weigh the empty 150mm by 150mm cube molds and base plate combined | √ | |
| d | Place the newly mixed concrete of 4.3 (j) in the mold in two layers using scoop, trowel or shovel | √ | |
| e | Ensure symmetrical distribution of concrete within the mold by moving the scoopful concrete around the top edge of the mold as the concrete slides from it | √ | |
| f | Vibrate each layer uniformly using the external vibrator specified in 4.1 above with supplementary surcharge plates. Consolidation using internal vibration is not possible as the size is small (ASTM C 192) | √ | |
| g | And then tamp the outsides of the mold lightly 10 to 15 times to close any holes left by vibrating and to release any large air bubbles | √ | |
| h | After vibrating the top layer strike off the surface of the concrete with a trowel, leaving the mold exactly filled | √ | |
| i | Weigh the mold filled with concrete in (h) above | √ | |
| j | The unit weight will be computed from the volume and weight of concrete in the mold | √ | |
| k | Cure the specimens as follows | | |
| | Protect the outside surface of the card-board molds from all contact with any sources of water for the first 24-hours | √ | |
| | Remove the specimens from the mold within 24 ± 8 -hrs after casting | √ | |
| | Moist cure the specimens at 23 ± 1.7 °C from the time of molding until the moment of test | √ | |
| 6.2 Flexural Specimens | | | |
| a | Place the forms (molds) as near as to the place where to store for 24-hours | √ | |
| b | Place the newly mixed concrete of 4.3 (j) in the forms (molds) in two layers using scoop, trowel or shovel | √ | |

| S/No | Activities | Mark | Remarks |
|------|---|------|---|
| c | Ensure symmetrical distribution of concrete within the mold by moving the scoopful concrete around the top edge of the mold as the concrete slides from it | √ | |
| d | Vibrate each layer uniformly using the external vibrator specified in 4.1 above with supplementary surcharge plates. Consolidation using internal vibration is not possible as the size is small (ASTM C 192) | √ | |
| e | And then tamp the outsides of the mold lightly 10 to 15 times to close any holes left by vibrating and to release any large air bubbles | √ | |
| f | After vibrating the top layer strike off the surface of the concrete with a trowel, leaving the mold exactly filled | √ | |
| g | Cure the specimens as follows | | |
| | Protect the outside surface of the card-board molds from all contact with any sources of water for the first 24-hours | √ | |
| | Remove the specimens from the mold within 24 ± 8 -hrs after casting | √ | |
| | Moist cure the specimens at 23 ± 1.7 °C from the time of molding until the moment of test | √ | |
| | At the end of the curing period, between the time the specimen is removed from curing until testing is completed, drying of the surface shall be prevented | √ | To avoid tensile stresses in the extreme fibers |
| | | | |

APPENDIX-B LABORATORY TEST RESULTS

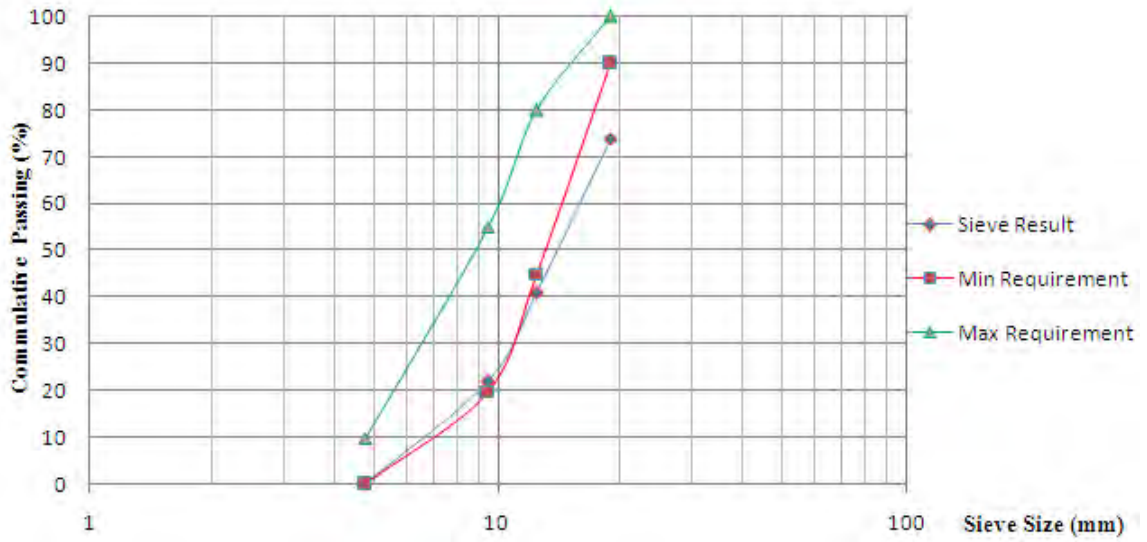


a) Before adjustment

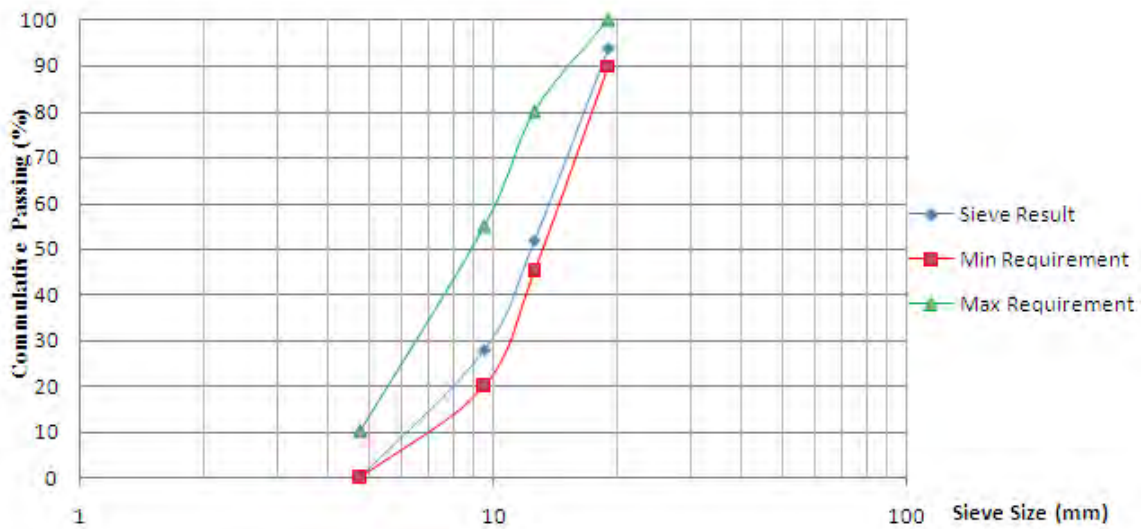


b) After adjustment

Figure B.1 Grading Chart of Sand



a) Before adjustment



b) After adjustment

Figure B.2 Grading Chart of Gravel

Table B-1 Unit Weight of Fresh Concrete

| Test series | Specimen code | Dimensions (cm) | | | Weight (kg) | Average unit weight (kg/m ³) |
|-------------|---------------|-----------------|-------|--------|-------------|---|
| | | Length | Width | Height | | |
| 1 | CJ 1-1 | 15.0 | 15.0 | 15.0 | 7.995 | 2374.16 |
| | CJ 1-2 | 15.0 | 14.9 | 15.0 | 8.040 | |
| | CJ 1-3 | 15.0 | 15.0 | 15.0 | 8.071 | |
| 2 | CJ 2-1 | 15.2 | 14.9 | 15.1 | 7.970 | 2351.04 |
| | CJ 2-2 | 14.9 | 15.1 | 15.1 | 7.970 | |
| | CJ 2-3 | 15 | 14.9 | 15.0 | 7.935 | |
| 3 | CJ 3-1 | 14.9 | 15.0 | 15.0 | 7.775 | 2319.14 |
| | CJ 3-2 | 15.0 | 14.8 | 15.0 | 7.855 | |
| | CJ 3-3 | 15.0 | 15.0 | 15.0 | 7.920 | |
| 4 | CJ 4-1 | 15.0 | 15.0 | 15.0 | 7.700 | 2231.66 |
| | CJ 4-2 | 15.1 | 15.1 | 15.2 | 8.085 | |
| | CJ 4-3 | 14.9 | 15.2 | 15.5 | 7.860 | |

Table B-2 Compression Test Results at 28-Days

| Test series | Specimen code | Maximum load | Maximum stress | Failure Mode |
|-------------|---------------|--------------|----------------|--------------|
| | | (kN) | (MPa) | |
| 1 | CJ 1-1 | 379.00 | 16.84 | Cone |
| | CJ 1-2 | 396.80 | 17.64 | Cone |
| | CJ 1-3 | 398.40 | 17.71 | Cone |
| 2 | CJ 2-1 | 419.10 | 18.65 | Columnar |
| | CJ 2-2 | 393.10 | 17.47 | Cone |
| | CJ 2-3 | 408.70 | 18.17 | Cone |
| 3 | CJ 3-1 | 368.39 | 16.39 | Cone |
| | CJ 3-2 | 358.10 | 15.82 | Cone |
| | CJ 3-3 | 355.90 | 15.82 | Cone |
| 4 | CJ 4-1 | 377.50 | 16.78 | Cone |
| | CJ 4-2 | 364.40 | 16.20 | Cone |
| | CJ 4-3 | 383.70 | 17.05 | Cone |

Table B-3 Bending Test Results at 28-Days

| Test series | Specimen code | Cracking load (kN) | Ultimate load (kN) | Failure Mode |
|--------------------|----------------------|-------------------------------|-------------------------------|---------------------|
| 1 | BJ 1-1 | 4.70 | 4.70 | Flexural |
| | BJ 1-2 | 4.80 | 4.80 | Flexural |
| | BJ 1-3 | Defected | Defected | |
| 2 | BJ 2-1 | 5.90 | 5.90 | Flexural |
| | BJ 2-2 | 6.00 | 6.00 | Flexural |
| | BJ 2-3 | 6.50 | 6.50 | Flexural |
| 3 | BJ 3-1 | 6.90 | 6.90 | Flexural |
| | BJ 3-2 | 6.80 | 7.50 | Flexural |
| | BJ 3-3 | Incorrect loading | Incorrect loading | |
| 4 | BJ 4-1 | 5.90 | 5.90 | Flexural |
| | BJ 4-2 | 5.30 | 5.50 | Flexural |
| | BJ 4-3 | 6.60 | 6.80 | Flexural |

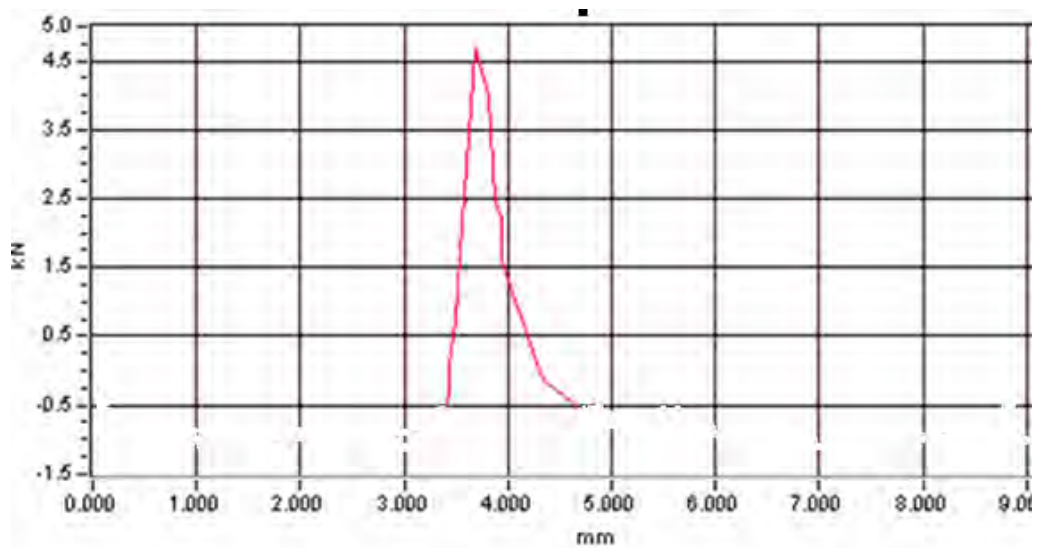
ANNEX

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 12-10-2001 E.C. Test date : 12-10-2001 E.C.
Label : BJ 1-1
Material type : JFRC
Machined : Ye
Load (kN) : 4.7 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

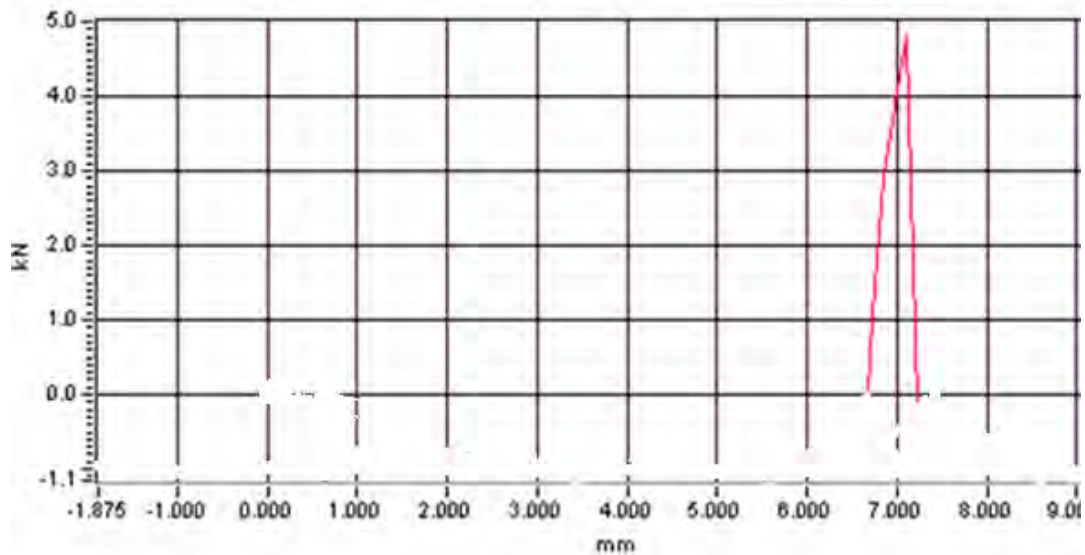
BJ 1: Certificate date : 12-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 12-10-2001 E.C. Test date : 12-10-2001 E.C.
Label : BJ 1-2
Material type : JFRC
Machined : Ye
Load (kN) : 4.8 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 1:

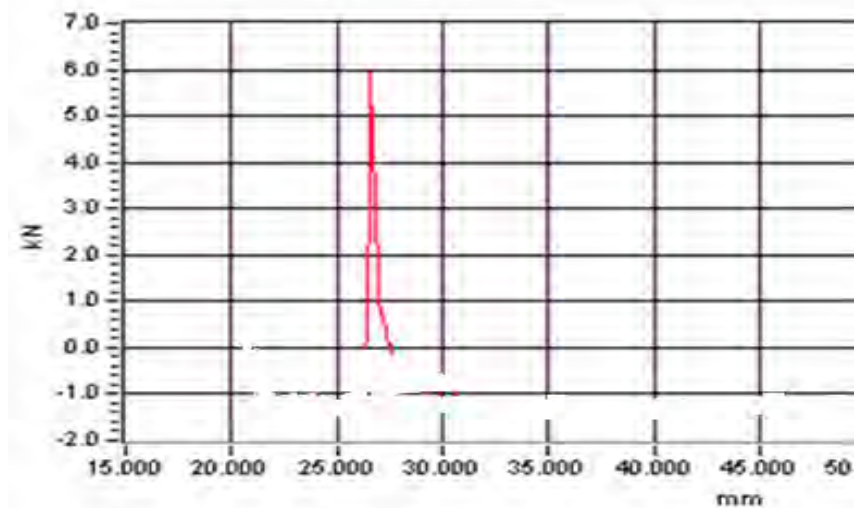
Certificate date : 12-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 14-10-2001 E.C. Test date : 14-10-2001 E.C.
Label : BJ 2-1
Material type : JFRC
Machined : Ye
Load (kN) : 5.9 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 2:

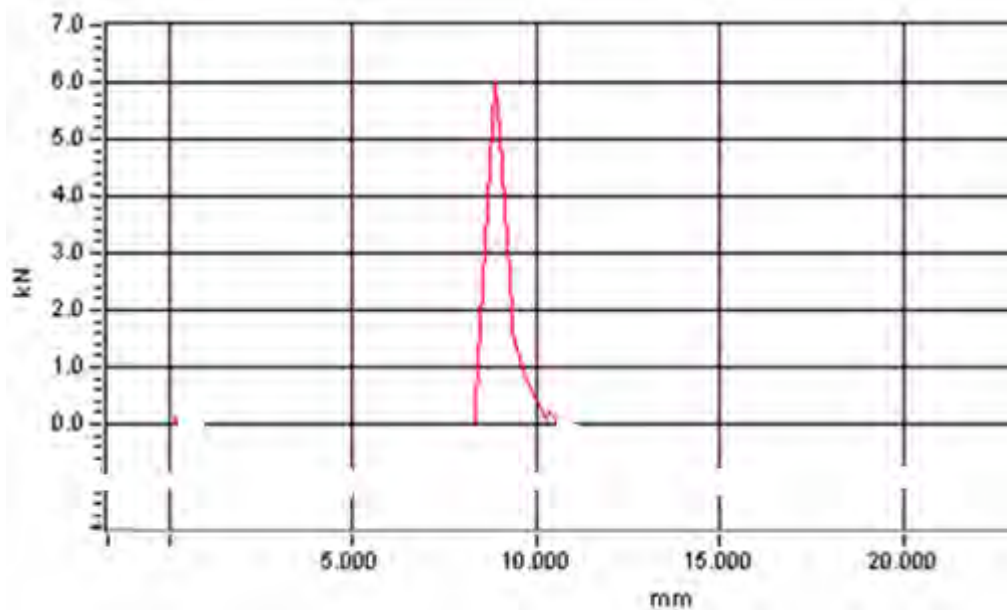
Certificate date : 14-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 14-10-2001 E.C. Test date : 14-10-2001 E.C.
Label : BJ 2-2
Material type : JFRC
Machined : Ye
Load (kN) : 6.0 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 2:

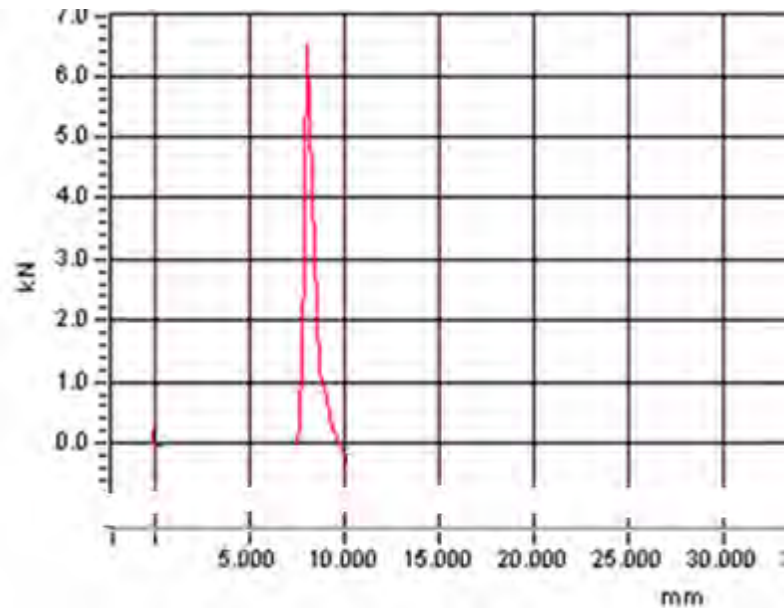
Certificate date : 14-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 14-10-2001 E.C. Test date : 14-10-2001 E.C.
Label : BJ 2-3
Material type : JFRC
Machined : Ye
Load (kN) : 6.5 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 2:

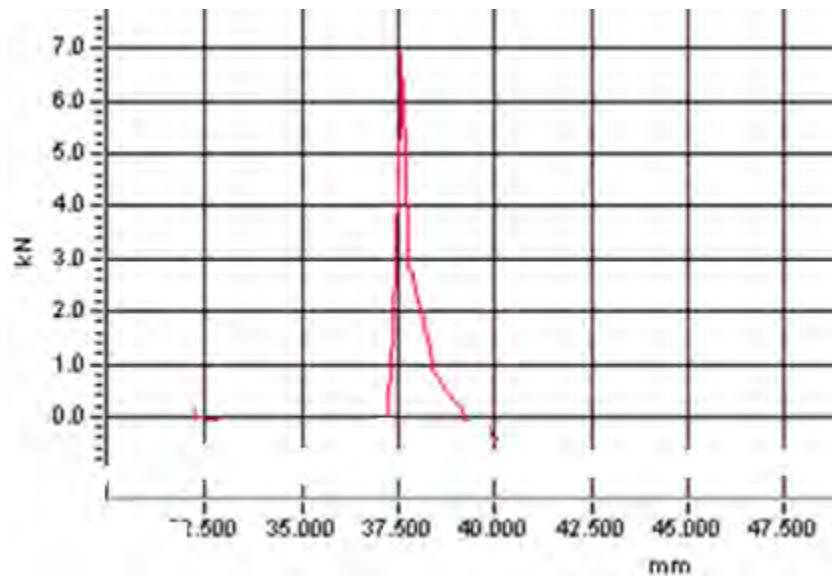
Certificate date : 14-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 13-10-2001 E.C. Test date : 13-10-2001 E.C.
Label : BJ 3-1
Material type : JFRC
Machined : Ye
Load (kN) : 6.9 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 3:

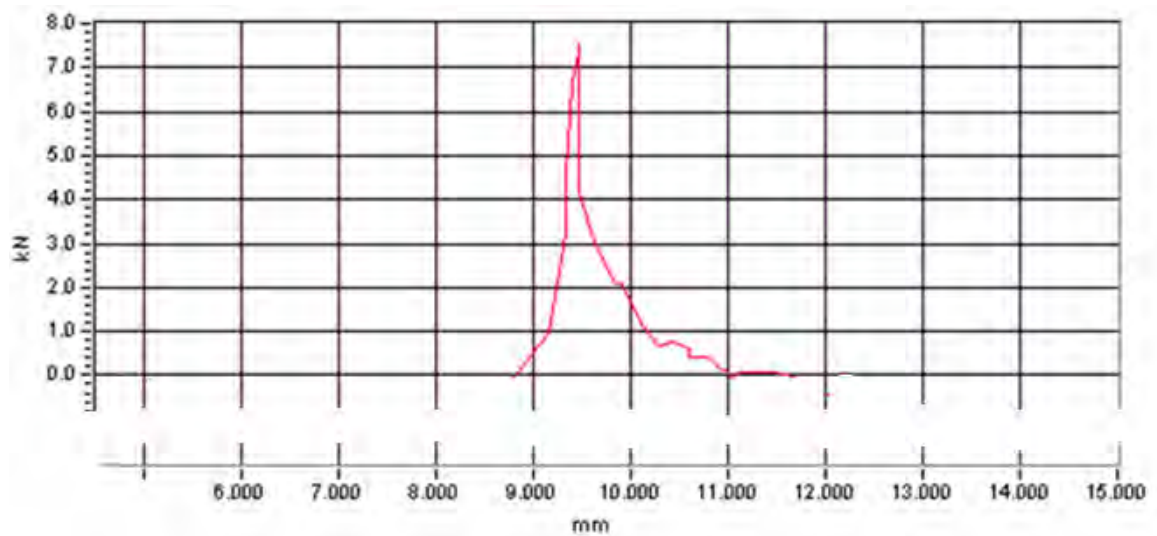
Certificate date : 13-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 13-10-2001 E.C. Test date : 13-10-2001 E.C.
Label : BJ 3-2
Material type : JFRC
Machined : Ye
Load (kN) : 7.5 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

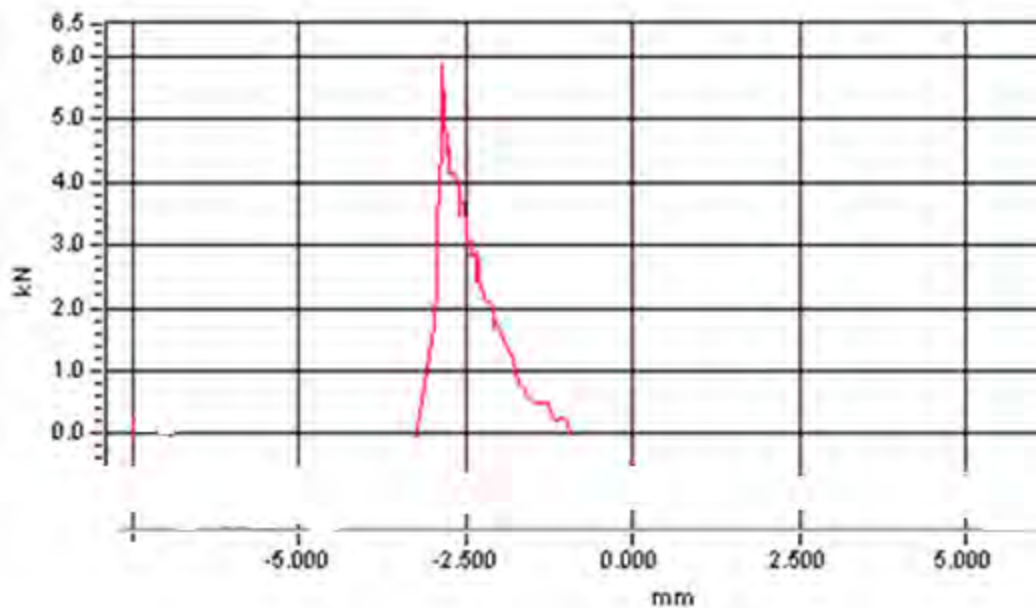
BJ 3: Certificate date : 13-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 13-10-2001 E.C. Test date : 13-10-2001 E.C.
Label : BJ 4-1
Material type : JFRC
Machined : Ye
Load (kN) : 5.9 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 4:

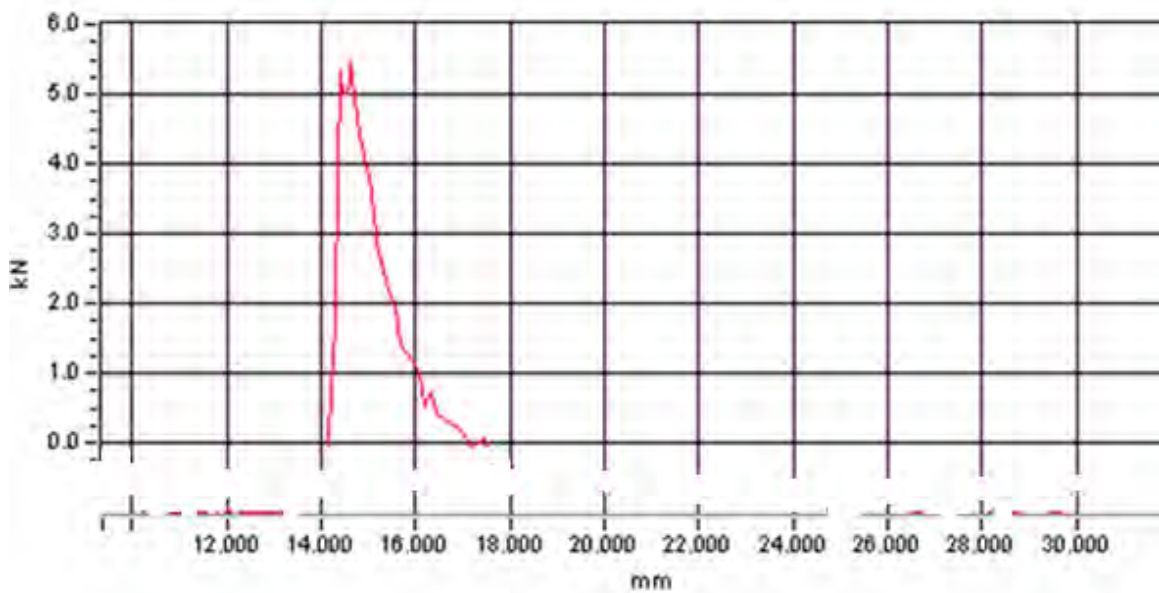
Certificate date : 13-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 13-10-2001 E.C. Test date : 13-10-2001 E.C.
Label : BJ 4-2
Material type : JFRC
Machined : Ye
Load (kN) : 5.5 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 4:

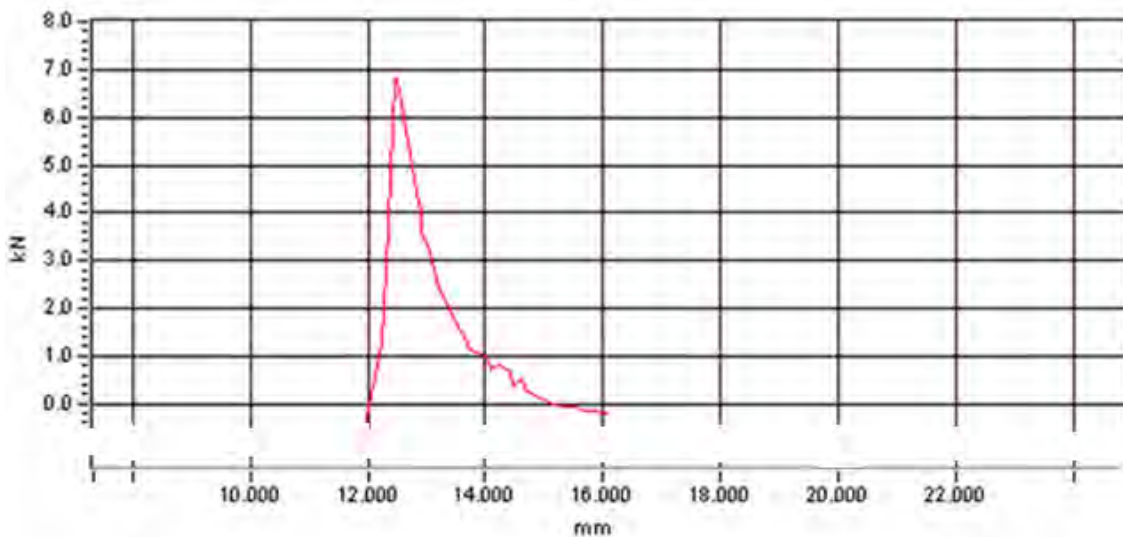
Certificate date : 13-10-2001 E.C.

TRANSVERSE TEST ON JFRC SPECIMENS

Client : ENYEW B.
Test organization : AAU, Faculty of Technology
Test location : AAU, Faculty of Technology, Civil Engineering Laboratory Section

SPECIMEN DESCRIPTION

Date received : 13-10-2001 E.C. Test date : 13-10-2001 E.C.
Label : BJ 4-3
Material type : JFRC
Machined : Ye
Load (kN) : 6.8 Span between rollers (mm): 440



Notes : The horizontal axis is scaled up by a factor of 10

Name : ENYEW BANTIE Position : Student, MSc in Structures

CERIFICATE IDENTIFICATION:

BJ 4:

Certificate date : 13-10-2001 E.C.

REFERENCES

- [1] A. M. Neville, *Properties of Concrete*, 3rd ed., London: Pitman Publishing Ltd., 1981.
- [2] F. M. Lea, *The chemistry of cement and Concrete*, 3rd ed., Edward Arnold Ltd, 1970.
- [3] G. S. Holister and C. Thomas, *Fibre Reinforced Materials*, London: Elsevier Publishing Co. Ltd., 1966.
- [4] G. E. Troxell, H. E. Davis and J. W. Kelly, *Composition and Properties of Concrete*, 2nd ed., New York: McGraw-Hill Inc., 1968.
- [5] H. F. Mark et al, Eds., *Encyclopedia of Polymer Science and Engineering*, 2nd ed., Vol. 6, New York: John Wiley and Sons, 1986.
- [6] H. F. Mark et al, Eds., *Encyclopedia of Polymer Science and Engineering*, 2nd ed., Vol. 7, New York: John Wiley and Sons, 1986.
- [7] R. S. P. Coutts, "From forest to factory to fabrication," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 31-47.
- [8] B. I. G. Barr, "Fibre reinforced concrete-where do we go from here?," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 3-11.
- [9] B. Chatveera and P. Nimityongskul, "Mechanical properties of sisal fibre-mortar composites containing rice husk ash," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1056-1072.

- [10] P. Jorillo Jr and G. Shimizu, "Coir fibre reinforced cement based composite. Part two: Fresh and mechanical properties of fiber-concrete," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1096-1109.
- [11] J.R. Al-Feel and N.K. Al-Layla, "Flexural strength of steel wool reinforced mortar," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 178-184.
- [12] K. K. Choi, H. Park and J. K. Wight, "Shear strength of steel fiber-reinforced concrete beams without web reinforcement," *ACI Structural Journal*, Jan/Feb 2007.
- [13] G. Shimizu and P. Jorillo Jr, "Coir fibre reinforced cement based composite. Part one: microstructure and properties of fibre-mortar," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1080-1095.
- [14] B. de Lhoneux and T. Avella, "Fibre-matrix interactions in autoclaved cellulose cement composites," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1152-1165.
- [15] H. Savastano Jr and V. Agopyan, "Transition zone of hardened cement paste and vegetable fibres," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1110-1119.
- [16] L. K. Aggarwal, "Durability studies on coir fibre reinforced cement boards," *Proc., Fourth RILEM International Symposium on Fibre*

Reinforced Cement and Concrete, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1120-1127.

- [17] M. J. E. Oliviera and V. Agopyan, "Effect of simple treatments on malva fibres for the reinforcement of Portland cement mortar," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1073-1079.
- [18] P. Soroushian and S. Marikunte, "Long-term durability and moisture sensitivity of cellulose fiber reinforced cement composites," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1166-1184.
- [19] E. K. Schrader, "Formulating Guidance for testing of fibre concrete in ACI Committee 544," in *Testing and Test Methods of Fibre Cement Composites*, Ed., R. N. Swamy, New York: Longman Inc., 1978.
- [20] S. S. Davydov, A. M. Ivanov and N. A. Moshchanskii, "General remarks on steel-reinforced polymer concretes," in *Steel Polymer Concrete Structural Construction*, S. S. Davydov and A. M. Ivanov, Eds., R. S. Ayaar, Trans., New Delhi: Amerind Publishing Co. Pvt. Ltd., 1975.
- [21] O. Braga Jr, "Glass wool waste-reinforced gypsum: efficiency of compaction and composite mechanical properties," *Proc., Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, Ed., R.N. Swamy, London: E and FN Spon, 1992, pp. 1044-1049.
- [22] F. Gorden et al, "Resistance changes during compression of carbon fiber cement composite," *Journal of Materials in Civil Engineering*, ASCE, vol. 15, no. 5, 2003, pp. 476-483.

- [23] A. Peled and A. Bentor, "Quantitative description of the pull-out behavior of crimped yarns from cement matrix," *Journal of Materials in Civil Engineering*, ASCE, vol. 15, no. 6, 2003, pp. 537-544.
- [24] P. H. Bischoff, "Tension stiffening and cracking of steel fibre-reinforced concrete," *Journal of Materials in Civil Engineering*, ASCE, vol. 15, no. 2, 2003, pp. 174-182.
- [25] F. Vossonghi et al, "Resistance of concrete protected by fabric to projectile impact," *Cement and Concrete Research*, vol. 37, no. 1, 2007, pp. 96-106.
- [26] K. G. Kuder et al, "Rheology of fiber-reinforced cementitious materials," *Cement and Concrete Research*, vol. 37, no. 2, 2007, pp. 191-199.
- [27] W. Yao and Z. Li, "Flexural behavior of bamboo-fiber-reinforced mortar laminates," *Cement and Concrete Research*, vol. 33, no. 1, 2003, pp. 15-19.
- [28] G. Li et al, "Properties study of cotton stalk fibre-gypsum composite," *Cement and Concrete Research*, vol. 33, no. 1, 2003, pp. 43-46.
- [29] ASTM- American Society for Testing and Materials, *Annual Book of ASTM Standards: Section 04.02-Concrete and Aggregates*, Printed in Baltimore, MD, 2002.
- [30] M. Nehdi, J. Duquette and H. El Damatty, "Performance of rice husk ash produced using a new technology as a mineral admixture," *Cement and Concrete Research*, vol. 33, no. 8, 2003, pp. 1203-1210.
- [31] Z. Li, L. Lijing and X. Wang, "Compressive and flexural properties of hemp fiber-reinforced concrete," *Journal of Fibers and Polymers*, The Korean Fiber Society, vol. 5, no. 3, 2004, pp. 187-197.

- [32] O. C. Choi and C. Lee, "Flexural performance of ring-type steel fibre-reinforced concrete," *Cement and Concrete Research*, vol. 33, no. 6, 2003, pp. 841-849.
- [33] Ministry of Works and Urban Development, *Ethiopian Building Code Standard: Structural use of concrete*, Addis Ababa, 1995.
- [34] J. G. MacGregor, *Reinforced concrete: mechanics and design*, New Jersey: Prentice Hall, 1988
- [35] J. A. Collins, *Failure of materials in mechanical design: analysis, prediction, prevention*, New York: John Wiley and Sons, Inc, 1993

DECLARATION

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university and all sources of materials used for the thesis have been duly acknowledged.

Name: Enyew Bantie Tamiru

Signature: _____

Institution: Addis Ababa University, Technology Faculty

Date of Submission: March, 2010