ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

Study on Mechanical Properties of Bamboo Fiber Reinforced Concrete

A Thesis Submitted to School of Graduate Studies of Addis Ababa University in Partial fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

(Construction Technology and Management)

By: Tesfaye Reta Degefa

Advisor: Prof. Abebe Dinku (Dr.-Ing)

April, 2017

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Tesfaye Reta Degefa

This is to certify that the thesis prepared by Tesfaye Reta, entitled "Study on Mechanical Properties of Bamboo Fiber Reinforced Concrete" is submitted in partial fulfillment of the requirements for the Degree of Master of Science (Construction Technology and Management), complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Declaration

I, the undersigned, declare that this thesis entitled "Study on Mechanical Properties of Bamboo Fiber Reinforced Concrete" is my original work. This thesis has not been presented in any other university and is not concurrently submitted in candidature of any other degree, and that all sources of material used for the thesis have been duly acknowledged.

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Abstract

Bamboo is a plant which is abundant in Ethiopia. About 67% of African Bamboo resources and more than 7% of the world's total bamboos are found in Ethiopia [14,17]. Bamboo is renewable and eco-friendly, as it consumes Nitrogen which could be a part of huge effort to prevent air pollution. This plant grows and reaches its maximum strength in just few years. A fiber of Bamboo is a natural fiber which serves to reinforce concrete materials and improves strength parameters of a concrete.

In this specific research, bamboo fibers were used as a reinforcing constituent material in production of fiber reinforced concrete. The experiments were performed on C-25 grade of concrete having target mean strength of 38.12MPa, water cement ratio of 0.59 and slump in the range of 30-60mm. Compressive strength, Flexural strength and Split tensile strength for 0%, 0.10%, 0.20% and 0.30% additions of bamboo fiber by weight of concrete were tested and compared with a plain concrete.

The standard 150mm cube compressive strength of BFRC with 0.10% and 0.20% addition of bamboo fiber by weight of concrete have showed an increment of 30.58% and 17.34% respectively. Whereas BFRC with 0.30% addition of bamboo fiber by weight of concrete showed a compressive strength reduction of 2.92% compared to plain concrete.

BFRC with 0.10% and 0.20% bamboo fiber addition by weight of concrete showed an increment in mean split tensile strength of 4.7% and 0.54% respectively; whereas 0.30% additions of bamboo fiber by weight of concrete showed split tensile strength reduction of 17.56% compared to plain concrete.

Mean Flexural strength of BFRC with 0.10%, 0.20% and 0.30% addition of bamboo fiber by weight of concrete has showed an increment by 3.57%, 4.84% and 6.77% compared to plain concrete respectively.

A slump test for BFRC reveals slump reductions of 41.67% for M_1 and M_2 and 50% reduction for M_3 compared to the reference plain concrete. Slump results for all mixes with BFRC were within the range of the slump in mix design. Fresh concrete densities for M_1, M_2 and M_3 also showed a slight reduction of 0.98%, 1.15% and 1.79% respectively.

Keywords: Bamboo, Fiber, Concrete, Reinforced Concrete, Mechanical properties

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List of Abbreviations

AAiT	Addis Ababa Institute of Technology
ACI	American Concrete Institute
AD	Anno Domino (In the year of the Lord, Years after the Christ's birth)
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BFRC	Bamboo Fiber Reinforced Concrete
CA	Coarse Aggregate
C-25	Concrete Grade with characteristic strength of 25MPa by 28th day
CoV	Coefficient of Variation
DOE	Department of Environment
EBCS	Ethiopian Building Code of Standard
ECBP	Engineering Capacity Building Programme
ES	Ethiopian Standard
FA	Fine Aggregate
FM	Fineness Modulus
FRC	Fiber Reinforced Concrete
M_0	Mix with 0.0% bamboo fiber
M_1	Mix with 0.1% bamboo fiber
M_2	Mix with 0.2% bamboo fiber
M_3	Mix with 0.3% bamboo fiber
MSL	Mean Sea Level
NaOH	Sodium Hydroxide
OPC	Ordinary Portland Cement
OD	Oven Dry condition
SSD	Saturated-Surface-Dry condition
UK	United Kingdom
USA	United States of America
V/V	Volume to Volume ratio

1. Introduction

1.1 General

Reinforced concrete constitutes different materials such as cement, sand, coarse aggregate, water and reinforcement bar. Among these, reinforcing bars provide a concrete with high tensile strength, ductility and flexural strength.

The concept of using fibers to improve the characteristics of construction materials is very old. The modern development of fiber reinforced concrete started in the early sixties [1].

There are 3 different types of fibers; synthetic, natural-organic and natural-inorganic fibers [2]. Synthetic fibers are of high initial cost and have detrimental effect to the eco-system [3]. Compared to natural-inorganic fibers, natural-organic fibers are renewable, environmentally friendly and economical as its production cost is very low [2]. Bamboo is a plant which is abundant in Ethiopia. It is renewable and eco-friendly, as it consumes Nitrogen which could be a part of huge effort to prevent air pollution. This plant grows and reaches its maximum strength in just few years [4]. A fiber of Bamboo is a natural organic fiber which serves to reinforce concrete materials and improves tensile strength of a concrete.

1.2 Statement of the Problem

Before environmental era emerges synthetic fibers were being used to provide a concrete good tensile strength as a reinforcement. But, currently the world is looking for eco-friendly construction materials with efficient cost and enormous abundances. About 67% of African Bamboo resources and more than 7% of the world's total bamboo are found in Ethiopia [14]. Yet, the potential use of bamboo and its fiber for engineering purpose is not fully utilized. There are certain factors which inhibit us from harnessing it; lack of technologists, lack of awareness, lack of instruments and frequent laboratory investigations.

1.3 Significance of the Research

The paper is intended to investigate potential use of bamboo fiber in concrete production. Bamboo fiber acts as reinforcement for the sake of improving mechanical properties of plain concrete. In doing so, bamboo fiber will enhance plain concrete to be resistant to tensile cracks, bending and fracture. Thus it's important to extend the concept of bamboo fiber addition into the conventional reinforced concrete as it saves percentage of reinforcement bars used in steel reinforced concrete production.

1.4 Research Objective

1. To study the potential use of bamboo fiber in improving the properties of fresh and hardened concrete
2. To quantify the effective percentage through investigating the effects of different percentage additions of bamboo fiber on the properties of freshly mixed concrete and hardened concrete.
3. To compare and contrast bamboo fiber reinforced concrete with plain concrete regarding basic characteristic mechanical properties; like compressive strength, flexural strength and split tensile strength.

1.5 Scope of the Research

The experiments in this specific research were conducted using highland bamboo (Yushinia Alphina) species. This specific research is also limited to investigate the mechanical properties of concrete mixes incorporating bamboo fiber as a reinforcement for a concrete grade designated C-25, at a constant water cement ratio of 0.59.

2. Literature Review

2.1 Introduction

Concrete is weak in tension and has a brittle character. The concept of using fibers to improve the characteristics of construction materials is very old. Early applications include addition of straw to mud bricks, horse hair to reinforce plaster and asbestos to reinforce pottery. Use of continuous reinforcement in concrete (reinforced concrete) increases strength and ductility, but requires careful placement and labour skill. Alternatively, introduction of fibers in discrete form in plain or reinforced concrete may provide a better solution. The modern development of fiber reinforced concrete (FRC) started in the early sixties. Addition of fibers to concrete makes it a homogeneous and isotropic material. When concrete cracks, the randomly oriented fibers start functioning, arrest crack formation and propagation, and thus improve strength and ductility. The failure modes of Fiber Reinforced Concrete are either bond failure between fiber and matrix or material failure [26].

2.2 Concrete Materials

Concrete is a product obtained artificially by hardening of the mixture of binding material (cement), fine aggregate (sand), coarse aggregate (gravel), Admixtures in some cases, and water, in a predetermined proportion. Since concrete is made from different materials which form different parts, it is known as a composite material. The cement and water form a paste that hardens and bonds the aggregates together into a coherent solid mass [6]. Performance of concrete depends on the quality of the constituent materials as well as on their proportion and on the process of construction that comprises: placing, compaction, and curing.

2.2.1 Aggregates

Aggregates, both fine and coarse, take about 65-75% by volume of concrete and are important ingredients in concrete production [5]. Aggregates are generally divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 9.5 mm (3⁄8 in.); coarse aggregates are particles retained on the 1.18 mm (No. 16) sieve and ranging up to 150 mm (6 in.) in size. The maximum size of coarse aggregate is typically 19 mm or 25 mm (3⁄4 in. or 1 in.). An intermediate-sized aggregates, around 9.5 mm (3⁄8 in.), are sometimes added to improve the overall aggregate gradation [6].

Aggregates may be broadly classified as natural or artificial, both with respect to source and method of production.

Natural sands and gravels are the product of weathering and the action of wind or water, while stone sands and crushed stone are produced by crushing natural stone. Screening and washing may be used to process aggregates from either of these categories. Aggregates may be produced from igneous, sedimentary, or metamorphic rocks, but the presence or absence of any geological type does not, by itself, make an aggregate suitable or unsuitable for use in concrete. The acceptance of an aggregate for use in concrete on a particular job should be based upon specific information obtained from tests used to measure the aggregate quality, or upon its service record, or both [7].

The gravel part of aggregates forms the skeleton of the concrete, providing its compression strength. The smaller sized aggregate fills the voids between the large particles, while the cement paste fills the smallest spaces, coats the aggregate particles and glues them together. The very fine cement particles also fill the smallest empty spaces, thereby giving the concrete its high density and impermeability.

2.2.2 Cement

Cement is a material with adhesive and cohesive properties which make it capable of binding two or more materials together into a solid mass. Cement when mixed with water form a paste which sets and hardens by means of chemical reaction called hydration, and retains strength and stability.

There are generally two types of cements; non-hydraulic and hydraulic cements. Hydraulic cements are types of cements which are able set and harden in water and give a solid mass; which doesn’t disintegrate (remain stable in water) [8]. The great majority of Portland cements made throughout the world are designed for general constructional use. The specifications with which such cements must comply are similar, but not identical in all countries and various names are used to define the material, such as OPC (Ordinary Portland Cement) in the UK, or Type I Portland Cement in the USA [9]. Cement type used in this specific research is an Ordinary Portland Cement because of its general use.

2.2.3 Water

Water is an important constituent in concrete. It chemically reacts with cement to produce the desired properties of concrete. Mixing water is a quantity of water that comes in contact with cement, impacts slump of concrete, and is used to determine water to cementitious materials ratio of concrete mixtures.

According to National Ready Mixed Concrete Association (NRMCA) of Maryland, mixing water in concrete includes the following:

- ◊ Batch water measured and added to a mixer,
- ◊ Ice free moisture on aggregates,
- ◊ Water included in a significant quantity with chemical admixtures, and
- ◊ Water added after batching during delivery at the jobsite.

Strength and durability of concrete is controlled to a greater extent by water cement ratio. Concrete strength increases when less water is used during preparation of the mix. Although the hydration process consumes a certain amount of water, wet concrete actually contains more water than required for the hydration reactions. The excess water is added to provide the wet mix with sufficient workability. Concrete needs to be workable so that it can be moulded into the desired shape and consolidated to the required density.

The quantity of water used divided by the amount of cement gives the water to cement ratio. Low water-cement ratio leads to high strength but low workability while a high water to cement ratio produces a low strength concrete but good workability. A careful balance of cement to water is therefore required when preparing the mix.

Good quality water is required for the mixing of concrete. Natural water that is drinkable and has not pronounced taste or odour can be used as mixing water for making concrete. Salt water should not be used for mixing concrete as it causes a significant reduction in strength and large variations in setting time [6].

2.2.4 Admixtures

Admixtures are those ingredients in concrete other than cement, water, and aggregates that are added to the mixture immediately before or during mixing. The major reasons for using admixtures are:

- To reduce the cost of concrete construction
- To effectively enhance existing properties of concrete
- To maintain the quality of concrete targeted during the stages of mixing, transporting, placing, and curing in adverse weather conditions
- To overcome certain emergency situations during concreting operations

The effectiveness of an admixture depends upon factors such as type, brand, and amount of cementing materials; water content; aggregate shape, gradation, and proportions; mixing time; slump; and temperature of the concrete [6].

2.3 Fibers

Fibers are small discrete reinforcing inputs produced from various materials like steel, glass, carbon and natural sources in various shapes and sizes [12]. Plain concrete possesses two major drawbacks as a structural material. They behave in brittle or semi brittle fashion and possess a very low tensile strength. Compared to other construction materials, it possesses a low specific modulus, limited ductility and little resistance to cracking. Micro cracks develop in the material during its manufacture due to inherent volumetric and micro structural changes, and an essential discontinuous, heterogeneous system thus exists even before any external load is applied. In addition to the low tensile strength, the material possesses little resistance to tensile crack propagation in turn results in low fracture toughness and limited resistance to impact and explosive loading. The successful use of the material in construction, therefore, depends in restricting the stresses in the material under working load condition, and cracking and deformation further limit the exploitation of the material [11].

It is necessary, therefore, to impart tensile resistance properties to a concrete structural member in order to use it as a load bearing material. This has been achieved since a hundred years or more, by the use of reinforcing bars. Reinforcement with iron bars enables concrete to carry tensile stresses quite successfully but the cracking strain of concrete is still so low that it cracks long before the wire is seriously loaded, and if a larger tensile load is put upon the combined system, an elaborate pattern of cracks appears in the concrete. In conventional concrete reinforcement the cracks are of great disadvantage. If cracks are small, they let water in and the steel is attacked. If cracks are large, the concrete falls out in pieces. To avoid these difficulties, one thing to do is to put the concrete permanently into compression, by putting the steel reinforcement permanently in tension. This provides tensile strength to the concrete members, but they do not increase the inherent tensile strength of concrete itself. Thus, the overall performance of the traditional reinforced concrete composite material is still effectively dictated by the individual performance of the concrete phase and the steel phase. This has led to the search for new materials particularly two phase composites in which the weak matrix is reinforced with strong stiff fibers to produce a composite of superior properties and performance [6, 11].

It has been found that addition of small closely spaced and uniformly dispersed fibers to concrete would act as crack arrestors and substantially improve the tensile strength and other properties of concrete. This type of concrete is called as fiber reinforced concrete [4, 26].

"Fiber reinforced concrete (FRC) can be defined as a composite material consisting of mixture of cement mortar or concrete and discontinuous, discrete, uniformly dispersed suitable fibers" [19]. The following articles will discuss types of fibers used in concrete.

2.3.1 Natural fibers

Natural fibers are fibers that are found in nature. Natural fibers can be classified as Organic or In-organic fibers. Natural organic fibers are derived from either plant or animal sources. The majority of useful natural textile fibers are plant derived with the notable exceptions of wool and, to a lesser extent, silk. Natural-inorganic fibers are discontinuous short fibers widely used to reinforce concrete. Many natural reinforcing materials can be obtained at low levels of cost and energy using locally available manpower and technical know-how. According to American Concrete Institute (ACI) natural fibers can be either processed or unprocessed.

Unprocessed natural fibers are available in reasonably large quantities in many countries and represent a continuously renewable resource. Unprocessed natural fibers require relatively small amounts of energy and technical know-how for their production compared to some other types of fibers. Coconut coir, sisal, sugarcane bagasse, bamboo, jute, wood, and vegetable fibers are typical examples of unprocessed natural organic fibers [12].

Wood cellulose is the most frequently used processed natural fibers, where it is obtained using Kraft process. This process involves cooking wood chips in a solution of sodium hydroxide. Cellulose, hemicellulose and lignin can be obtained by bleaching [13]. The below shown Table 2.1 describes typical properties of naturally occurring fibers [27].

Table 2.1: Typical properties of natural fibers [27]

Fiber type	Coconut	Sisal	Sugarcane bagasse	Bamboo	Jute	Flax	Elephant grass	Water reed	Wood fiber (Kraft pulp)
Fiber Length (mm)	50-100	N/A	N/A	N/A	175-300	500	N/A	N/A	2.5-5.0
Fiber diameter (mm)	0.1-0.4	N/A	0.2-0.4	0.05-0.4	0.1-0.2	N/A	N/A	N/A	0.03-0.08
Specific gravity	1.12-1.15	N/A	1.2-1.3	1.5	1.02-1.04	N/A	N/A	N/A	1.5
Modulus of elasticity (GPa)	19-26	13-26	15-19	33-40	26-32	100	5.0	5.0	N/A
Ult. tensile strength (MPa)	120-200	275-570	180-290	350-500	250-350	1000	180	70	700
Elongation at break (%)	10-25	3-5	N/A	N/A	1.5-1.9	1.8	3.6	1.2	N/A
Water absorption (%)	130-180	60-70	70-75	40-45	N/A	N/A	N/A	N/A	50-75

N/A: Not available

2.3.2 Synthetic fibers

Synthetic fibers are man-made fibers resulting from research and development in the petrochemical and textile industries [6]. These fibers are derived from organic polymers which are available in a variety of formulations. There are two different physical fiber forms: monofilament fibers and fibers produced from fibrillated tape. There are two different synthetic fiber volumes used in application, namely low volume percentage (0.1-0.3% by volume), and high volume percentage (0.4-0.8% by volume). Most synthetic fibers applications are at 0.1% by volume [13]. Fiber types that have been tried in Portland cement concrete based matrices are: acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. Synthetic fibers can reduce plastic shrinkage and subsidence cracking and may help concrete after it is fractured.

Problems associated with synthetic fibers include: low fiber-to-matrix bonding; inconclusive performance testing for low fiber-volume usage with polypropylene, polyethylene, polyester and nylon; a low modulus of elasticity for polypropylene and polyethylene; and the high cost of carbon and aramid fibers [6, 13].

2.3.3 Glass fibers

The first research on glass fibers was in the early 1960's used as conventional borosilicate glass (E-glass) and soda-lime-silica glass fibers (A-glass). Glass fibers have high modulus and high strength to develop strong bond with the concrete. The test results showed that alkali reactivity between the E-glass fibers and the cement-paste reduced the strength of the concrete. Glass fibers that are used in concrete must contain minimum of 16% of zirconia for alkali resistance. Fiber content in glass fiber reinforced concrete is about 4% to 6% by volume [6, 28].

2.3.4 Steel fibers

Steel fibers are short, discrete lengths of steel with an aspect ratio (ratio of length to diameter) from about 20 to 100, and with any of several cross sections. Some steel fibers have hooked ends to improve resistance to pullout from a cement-based matrix. Steel-fiber volumes used in concrete typically range from 0.25% to 2%. Volumes of more than 2% generally reduce workability and fiber dispersion and require special mix design or concrete placement techniques. Steel fibers have a relatively high modulus of elasticity. Their bond to the cement matrix can be enhanced by mechanical anchorage or surface roughness and they are protected from corrosion by the alkaline environment in the cement matrix [6, 12].

2.4 Bamboo Plant

Bamboo is neither grass nor wood, while it has two of their characteristics. It belongs to the family of the *Bambusoideae*. It is estimated that 60–90 genera of bamboo exist, encompass approximately 1100–1500 species and there are also about 600 different botanical species of bamboo in the world. Bamboo mainly grows in tropical and sub-tropical regions of Asia, Latin America and Africa [14]. Bamboo, itself is very strong in its longitudinal direction due to strong fiber bundles penetration. The bamboo culm, in general, is a cylindrical shell, which is divided by transversal diaphragms at the nodes. Bamboo shells are orthotropic materials with high strength in the direction parallel to the fibers and low strength perpendicular to the fibers. The thickness and strength of bamboo, however, decreases from the base to the top of the bamboo culm [15, 18]. It is obvious that ecological materials satisfy fundamental requirements like pollution prevention and cost minimization. The use of agricultural by-products such as rice husk, coconut fibers, sisal and bamboo fibers plays a great role in minimizing energy consumption, conserving non-renewable natural resources, reducing pollution and maintaining a healthy environment [15]. Bamboo is the core of these materials that fulfills these advantages.

Different researchers conduct tests on the mechanical properties for different species of bamboo fibers as a function of age, moisture content, density, etc. The optimum strength value occurs between 2.5 to 4 years of bamboo age [16]. The Ethiopian natural bamboo forest covers about 1 million hectares, which is about 7% of the world total and 67% of the African bamboo forest area. Different bamboo species are available in Ethiopia. Ethiopia has Africa's biggest bamboo resources and this plant can be harvested in sustainable cycles on 30%-40% of the mature culms every two years [14]. The total resource base of Ethiopia is confined to two indigenous bamboo species out of more than 1500 species of bamboo in the world and 43 species in Africa. The highland bamboo (Yushania Alpina), covers 15% and the monotypic genus lowland bamboo (Oxythenantera Abyssinica), covers 85% [14].

2.4.1 Highland Bamboo (Yushania Alpina, Arundinaria Alpina)

The highland Bamboo species is botanically known as Yushania alpina. The species was formerly classified under genus Arundinaria, and older literatures refer to this bamboo species using the name Arundinaria alpina. The local name for this bamboo species in Amharic is known as kerkeha [19]. The species grows naturally in ecological zones of the country 2200-4000 meters above sea level. Distribution of Y. alpina natural forests and man-made plantations in Ethiopia includes major places and localities of central and southern, south-western and north western parts of the country namely Hagere-selam, Injibara, Gojjam, Shewa, Kefa, Gamo-gofa, Sidamo, Bale, Jima (Agaro, Gera), and Bore/Gujji [17, 20]. Y. alpina occurs in scattered populations on mountains from southern Sudan and Ethiopia to Malawi. Out of Ethiopia, it is available in Kenya southern Sudan, Congo, Zaire, Rwanda, Uganda, Burundi, Tanzania, Cameroon, Malawi and Zimbabwe [20].

Highland bamboo (Y. alpina, Arundinaria alpina) has the following properties [20, 21];

- It grows at an altitude of 2200-4000m above MSL
- It needs 1500-2000mm rainfall
- Grows in 10-20^{o}C temperature
- It attains mean height and base diameter of 12-20m and 8-20cm respectively
- Hollow, monopodial and evergreen
- It is single stemmed form and
- Culms are fully mature after 3 years of emerge from the soil

2.4.2 Lowland Bamboo (Oxytenanthera Abyssinica)

O. Abyssinica natural forests are available in Gambella, Asossa, Dedessa, Pawe, West Wollega (Begi, Nejo, Gimbi, Guten, Didessa Valley, Kelem), north of Nekempte/Hinde and the western part of the country along major river valleys and in areas bordering Sudan. O.Abyssinica is distributed throughout tropical Africa outside the humid forest zone. Out of Ethiopia it is available in Senegal, Eritrea, Malawi, Angola, Mozambique, South Africa, Zimbabwe and Zambia [17,20].

O. Abyssinica grows within deciduous, savanna woodlands of western Ethiopia associated with grasslands. These bamboo species have the following properties [20];

- It grows at an altitude of 500-1600 above MSL
- It needs 1150mm rainfall and 20-27^{o}C temperature
- These bamboo species can even grow on poor volcanic soils where the rainfall is only 600mm and the temperature is above 35^{o}C.
- It attains a mean height and base diameter of about 6-8m and 4-8cm; respectively
- It is monotypic species of clumping form

In Ethiopia, in the past and even in present, the economic potential of bamboo has not been explored and the role of bamboo resources in national economies is negligible. However, now a day, bamboo has been used in traditional ways in the country side a little bit for the scaffolding, construction of houses, fuel feed houses, feed fodder, beehives, hats, mats, baskets, handicrafts, small furniture and other numerous products [17].

2.5 Bamboo Fiber

Bamboo has many culms. There is a variety between different culms on stiffness, strength and fracture toughness. The culm of a bamboo plant is a ligno-cellulosic natural functionally graded composite material. Fibers are densely located around the outer cortex and similarly on the top of the culm. As a result, when we examine bamboo timber; from inner to the outer and from the bottom culm to the top, the mechanical strength of the bamboo is augmenting [19].

2.5.1 Properties of bamboo plant

2.5.1.1 Physical and mechanical properties

Specific gravity: it is a measure of density of a substance in comparison with density of water. Specific gravity of bamboo varies between 0.4 and 0.8 depending mainly on anatomical structure [22]. The outer part of the bamboo culm has a higher specific gravity than the inner part. Specific gravity increases along the culm from bottom to the top [23].

Moisture content: moisture of bamboo varies vertically from the bottom to the top portion and horizontally from the outer layer to the inner layers. Bamboo possess very high moisture content and green bamboo may have 100% moisture content (oven-dry weight basis) and can be as high as 155% for the innermost layers and 70% for the peripheral layers.

Age of bamboo: fiber length and fiber diameter increases with increases of age of bamboo and strength of bamboo increases with an increment of age. The optimum strength value occurs between 2.5 and 4 years and decreases at the later ages [19].

Nature of fibers: Bamboo fibers are long and tapered at their ends. They contribute 60-70% of the weight of total culm tissue. Fiber length showed considerable variation within species. Fibers in bamboos are grouped in bundles and sheaths around the vessels. The epidermal wall consists of an outer and inner layer; of which the latter is highly lignified [22].

2.5.1.2 Chemical properties

The main chemical constituents of bamboo culms are cellulose, hemi-cellulose and lignin; minor constituents consist of resins, tannins, waxes and inorganic salts. Composition varies according to species, condition of growth, age of bamboo plant and part of the culm. Bamboo has 60% cellulose and considerably about 32% of lignin [23, 25]. The bamboo fiber is often brittle compared with other natural fibers, because the fibers are covered with lignin. Therefore, a devised process should be adopted to extract the bamboo fibers for reinforcement of composite materials [24].

2.5.2 Extraction process of bamboo fiber

The chemical constituents of bamboo are primary cellulose, hemi-cellulose and lignin. The bamboo has 60% cellulose and a considerably high percentage of lignin (about 32%). The bamboo fiber is often brittle compared with other natural fibers, because the fibers are covered with lignin.

Therefore, a devised process should be adopted to extract the bamboo fibers for reinforcement of composite materials. Bamboo fibers can be extracted in different ways. Some of them are explained below.

Chemical processing: It is basically hydrolysis alkalization. The crushed bamboo is cooked with the help of Sodium hydroxide (NaOH) into a form of regenerated cellulose fiber. Hydrolysis alkalization is then done through carbon disulfide combined with multi-phase bleaching. Due to high consumption of energy, health problems and pollution aspects; chemical processing is not environmental friendly, since it is preferred by many manufacturers as it is a less time consuming process [29].

Mechanical processing: In this method, the crushed bamboo is treated with biological enzymes. This breaks the bamboo into a mushy mass and individual fibers are then combed out. Although expensive, this process is eco-friendly [29].

Steam-explosion processing: Raw bamboo was first cut into bamboo culms with 70-80cm in length by saw machine, and put into an autoclave with over-heated steam at 175^0C and at a pressure of 0.7-0.8 MPa for 60 minutes. Then, the steam was suddenly released for 5 minutes and the cycles of sudden-steam release were continuously repeated for 9 times to assure the complete facture of cell walls. Finally, they were washed in hot water with addition of soap at $90\text{-}95^0$C for 15 minutes to remove ash and dried in the oven for 24 hours at 105^0C [29].

2.6 Previous Works Related to Fiber Reinforced Concrete

Adding reinforcement to the mixer in the form of fibers, simply like adding aggregates or admixtures, to create a homogeneous, isotropic, moldable structural material is a dream that started more than a century ago. The first patent (1874) on fiber reinforced concrete seems to be due to A. Berard from California who suggested the use of granular waste iron in a concrete mix to create an artificial stone (Antoine E. Naaman, 1985).

In 1990, G.Chanviliard, N.Banthia and P.C. Aitcin proposed in their work normalized load-deflection curve for fiber reinforced concrete under flexure as a simple and practical technique of treating the load versus deflection plots. The effect of fibers is quantified by the toughness index. The load-deflection curve is redrawn with the assigned values of both the load and displacement at first crack. The curve is convenient to assess the residual strength of a member and to conceptualize the efficiency of a given fiber in the context of its structural performance.

Satyanarayana K.G., Sukumaran K., Mukhenjee P.S., Pavithran C. & K.Pilia S.G. reported on natural fiber -polymer composites. Natural fibers such as jute, coir, banana, sisal, cotton, pineapple, palm-tree-frond and coconut tree based fibers incorporated in low modulus matrix like polyester yield materials with better properties, suitable for various applications. However, although their poor strength due to low density they can lead to high specific strength properties if incorporated in a polymeric matrix. Moreover, they have also high resistance to crack propagation.

Balguru and Shah (1992) reported that the modern developments of using only straight steel fibers began in the early 1960's. Till now, wide ranges of the other type of fibers are used in cement matrices.

A.Nanni and N.Meamaian presented an experimental study on distribution and opening of fibrillated polypropylene fibers in concrete, while P.Rossi described mechanical behavior of metal-fiber reinforced concrete .

In 992, Victor C. Li presents a preliminary micromechanical model, which captures the salient features of some of these concepts and relates them to experimentally observed compressive strength variations in fiber reinforced cementitious composites.

The 1993, work of Seung Bum Park studying mechanical properties together with the creep behavior of the carbon fiber reinforced polymer cement composites can be mentioned.

The 1994, analytical model for predicting the response of steel fiber concrete under biaxial compression up to failure was presented by Tan K.H, Murugappan K. and Paramassivam. An analytical method predicting the moment-curvature and load-deflection relationships for beams made of fiber concrete containing conventional reinforcement was presented by Samer Ezeldin A. and Shiah T.W. He reported the algorithm capable of predicting both immediate and long-term behavior of tested beams.

Huang Chenkui & Zhao Guofan studied tensile compressive, flexural strength, toughness and fatigue strength of steel fiber reinforced concrete containing large aggregates with maximum size of 40mm. They derived an equation predicting the fatigue flexural strength of fiber concrete containing larger crushed stone.

In 1999, Yining Ding and Wolfgang Kusterle demonstrated that the use of fiber reinforcement in concrete or shotcrete can greatly enhance the punching shear capacity, flexural ductility, toughness, and therefore possibly replace the conventional steel mesh reinforcement.

Savastano H., Warden P.G. and Coutts R.S.P. (2000), in their study on waste fiber as reinforcement for cement based composites showed that Eucalyptus grandis waste have an acceptable performance as reinforcement in cement-based composite materials for low-cost housing applications. This fact confirms again the potential applications of concrete reinforced with natural fibers, which are very abundant in developing countries.

Fiber reinforced concrete is thus a relatively new material in which steel or other fibers are introduced as micro reinforcements. By the introduction of steel or other fibers, not only the occurrence of the first crack is delayed but flexural strength, modulus of rupture, fatigue, impact strength, shock resistance, shear and torsional strength, ductility, and failure toughness are also greatly improved (Prakash K. B. 1998).

The idea that concrete can be strengthened by the inclusion of fibers was also put forward by Porter in 1910, but little progress was made in the development of this material until 1963, when Romualdi and Batson (1963) published their classical paper on the subject.

Based on the principles of fracture mechanics, study on closely spaced fibers acting as crack arresters have established that the increase in strength is inversely proportional to the square root of fibers spacing. Since then, there has been a wave of interest in fiber reinforced concrete and several interesting experiments have been carried out using different fiber products.

A French patent dated 1918 by Alfsen H. describes a process to improve the tensile strength of concrete by uniformly mixing small longitudinal bodies (fibers) of iron, wood or other materials. It also suggests that the surface of these fiber elements must be rough or roughened and, if possible, their ends bent in order to provide better adherence to the concrete (Antoine E. Naaman, 1985).

Ramesh M. et al., investigated the mechanical properties of sisal, jute and glass fiber reinforced polyester composites. They observed that the addition of glass fiber into jute fiber composite resulted in maximum tensile strength. In the same way, they have observed that jute and sisal mixture composites sample is capable of having maximum flexural strength; whereas sisal fiber composite sample have showed maximum impact strength.

Hemalata Jena et al. [10] studied the effect of bamboo fiber composite filled with cenosphere. They have reported that the impact property of bio-fiber reinforced composite is greatly influenced by addition of cenosphere as filler and lamina. For a given laminated composite, the impact strength is increased with addition of filler up to a certain limit and after further addition filler impact strength is decreased. The results reveal the sensitivity of the impact properties to the concentration of the fillers.

Shin F.G., Xian X.J.; Zheng, W.P., Yipp, M.W. analyzed the mechanical properties and microstructure of bamboo epoxy composites on Journal of Materials Science 24(10): 3483-3490). Unidirectional bamboo epoxy laminates of varying laminae number were experimentally evaluated for their tensile, compressive, flexural, and interlinear shear properties. The disposition of bamboo fiber, parenchymatous tissue, and resin matrix under different loading conditions was examined. Mechanical properties were comparable to those of glass-fiber composites. The fracture behavior of bamboo epoxy under the different loading conditions was evaluated using acoustic emission techniques and scanning electron microscopy. The fracture mode was found to be similar to carbon and glass reinforced composites.

2.7 Working Mechanisms

When the weak matrix in concrete is reinforced with fibers, it will be uniformly distributed across its entire mass, gets strengthened, thereby rendering the matrix to behave as a composite with properties significantly different from plain concrete. When concrete cracks, the randomly oriented fibers start functioning, arrest crack formation and propagation thus improve strength and ductility. The mechanical properties and geometry of both the fibers and matrix significantly affect the load transfer mechanism during the fiber pull-out process from the hardened cement paste matrix to the fiber by shear deformation at the paste or fiber interface [32].

The magnitude of improvement in toughness is strongly influenced by fiber concentration and resistance of fibers pull-out. There should be a balance in optimizing the bond between the fiber and the matrix. Fiber-matrix bond can be achieved by avoiding balling of fibers through approving random distribution of fibers at dry-mixing; avoiding long and fibrillated fibers and minimizing pull-out of fibers etc. If the fibers have a weak bond with the matrix, they can slip out at low loads and they do not contribute to bridge the cracks [31].

ACI committee suggests an acceptable fiber volume ratio from 0.25% to 2.0%, to ensure an adequate balance between structural benefit and workability. Fiber pull-out is a desired mode of failure, as it dissipates energy. The principal role of the fibers is to bridge across the cracks that develop when the strain of the composite has exceeded the ultimate strain capacity of a brittle matrix. In the post cracking zone, the fibers may increase the strength of a concrete over that of the matrix by transferring loads across the crack [30].

2.7.1 Orientation of fibers

Fiber reinforced concrete is the composite material containing fibers in the cement matrix in an orderly manner or randomly distributed manner. Its properties would obviously, depends upon the efficient transfer of stress between matrix and the fibers. One of the differences between steel reinforcement and fiber reinforcement is that in steel reinforcement, bars are oriented in the direction desired while fibers are randomly oriented. Eventhough its difficult to align fibers parallel or perpendicular to the direction of load application, fibers aligned parallel to the applied load offered more tensile strength and toughness than randomly distributed or perpendicular fibers

2.7.2 Workability and compaction of concrete

Incorporating fibers in concrete decreases the workability considerably. This situation adversely affects the consolidation of fresh mix. Even prolonged external vibration fails to compact the concrete. The fiber volume at which this situation is reached depends on the length and diameter of the fiber.

Another consequence of poor workability is non-uniform distribution of the fibers. Generally, the workability and compaction of standard the mix is improved through increased water/cement ratio or by the use of some kind of water reducing admixtures.

2.7.3 Aspect ratios of fibers

Fiber is a small piece of reinforcing material possessing certain characteristics properties. They can be circular or flat. The fiber is often described by a convenient parameter called "aspect ratio". The aspect ratio of the fiber is the ratio of its length to its diameter. Increase in the aspect ratio of the fiber usually segments the flexural strength and toughness of the matrix. However, fibers which are too long tend to "ball" in the mix and create workability problems.

2.7.4 Mixing of fiber reinforced concrete

Mixing of fiber reinforced concrete needs careful conditions to avoid balling of fibers, segregation and in general the difficulty of mixing the materials uniformly. Increase in the aspect ratio, volume percentage and size and quantity of coarse aggregate intensify the difficulties and balling tendency. Fibers content added in excess of its recommendable ranges and with greater aspect ratio is difficult to mix. It is important that the fibers are dispersed uniformly throughout the mix; this can be done by the addition of the fibers before the water is added. When mixing in a laboratory mixer, introducing the fibers through a wire mesh basket will help the evenly distribution of fibers. For field use, other suitable methods must be adopted.

2.8 Summary of Literature Review

It was identified by different literatures that plain concrete possesses drawbacks as structural material. They behave in a brittle and semi-brittle fashion and possess very low tensile strength, low specific modulus, limited ductility and little resistance to crack formation and propagation. It was forwarded by literatures that these concrete drawbacks studied to be improved with the addition of short and discrete fibers as reinforcement.

Scholars have made different studies of adding reinforcement to a concrete mix in the form of fibers like granular waste iron, straight steel, plastic, glass and natural material fibers. Among these fibers, different studies have showed that the uses of natural fibers as a concrete reinforcement were acknowledged because they are ecological materials which satisfy pollution prevention and maintain healthy environment.

Harvesting mature culms and air-drying in a well ventilated shade for several weeks is common in processing of bamboo culm for most uses. Harvesting culms will be during the dry season where starch content in the culm lowers and make them less susceptible to borers attack. Making sure the culms doesn’t have direct contact with the soil, keeping bamboo culms upright can reduce the starch content [33]. It is clear from the literature review that different researchers have conducted tests on the mechanical properties for different species of bamboo fibers as a function of age, moisture content, density, etc. Bamboo plant matures and gains its optimum strength in between 2.5 to 4 years. Bamboo plant culm is strong in its longitudinal direction as the fibers are oriented along these directions [19].

Through the extensive literature review it has been identified that there is no such a comprehensive study conducted on the effect of mechanical properties of hardened concrete made with bamboo fiber addition as a reinforcement. Thus, the paper is intended to examine the potential use of bamboo fiber as concrete ingredient. The paper is also intended to investigate the effect of percentage bamboo fiber addition by weights of concrete and compare bamboo fiber reinforced concrete with plain concrete regarding mechanical properties.

For the sake investigation, experimental program with regard to bamboo fiber addition as reinforcement in the concrete mixture to investigate the effect of mechanical properties like compressive strength, split tensile strength and flexural (bending) strength were setup according to the following session of the research document.

3. Materials Preparation and Methodologies

3.1 Introduction

Concrete is a composite material composed of cement, sand as fine aggregate, crushed rock as coarse aggregate, water and admixture. It's obvious that, concrete can be produced through mixing of concrete ingredients, but the important point to bear in mind is producing acceptable concrete quality with a reasonable economy. To produce acceptable quality, it's important to make physical characteristic tests on concrete making materials before any concrete experiments are carried out. So, this chapter elaborates concrete making materials used for the research and their physical test results conducted from the experiment, mix design and proportioning, and concrete production process.

3.2 Materials Used for the Experiment

3.2.1 Cement

Cement from different sources may have different properties which in turn will influence properties of concrete mix. Ordinary Portland Cement is designed for a general use of construction work throughout the world. From locally produced cements Derba Ordinary Portland Cement has been used in this specific research.

3.2.2 Fine aggregate

In this specific research work, local river sand was used as fine aggregate. Physical properties of fine aggregates like specific gravity and absorption capacity (ASTM C 128), fineness modulus (ASTM C 136), silt content and moisture content (ASTM C 566) are determined.

3.2.3 Coarse aggregate

Basaltic crushed rock was used as coarse aggregate in sample preparation for this specific experimental study. The maximum aggregate size of coarse aggregate is 19 mm. Physical properties of coarse aggregate; like specific gravity and absorption capacity (ASTM C 127), moisture content (ASTM C 566) and sieve analysis (ASTM C136) are determined.

3.2.4 Bamboo fiber

Bamboo plants for this study were collected from SNNP region, Gurage Zone, a place called Sebatbet. These bamboo plants are of highland bamboo (Yushinia Alphina) species. Bamboo fiber extraction has followed a Mechanical and Physico-chemical procedures as it is discussed in the methodology session.

3.2.5 NaOH and ethanol

Soda cooking liquor was prepared from concentrated solution of NaOH by serial dilution with de-ionized water. Soda-ethanol pulping liquor was prepared by mixing equal volume of respective solution of NaOH with mixture of Ethanol water, 60/40 (V/V).

3.3 Methodologies

All constituent materials used in producing concrete samples have been prepared and their respective physical properties were performed to approve their appropriateness. Constituent materials for normal grade concrete designated as C-25; having target mean strength (38.12MPa) were proportioned using DOE (Departments of Environment) mix design method. Samples for flexural strength tests, split tensile strength test and compressive strength test were casted, demoulded, cured with ponding and tested on their respective dates.

3.3.1 Materials preparation

Ordinary Portland Cements supplied from Derba Cement Factory has been used for this specific research throughout the whole experiment. The cement is produced as per CEM-I-42.5 grade and contains 95% clinker and 5% gypsum.

Aggregate samples have been prepared in accordance with the test requirements; and hence mined river sand samples were collected from suppliers; basaltic crushed stone samples were also collected from manufacturers. It is very important to obtain the right type and quality of aggregates on site. They should be clean, hard, strong, durable and graded in size to achieve utmost economy from the paste. Therefore, to judge the quality and physical characteristics of the aggregates, physical tests were conducted for both fine and coarse ingredients.

Bamboo fibers were prepared by extracting bamboo plant culm through mechanical and physico-chemical extraction process. Bundles of bamboo are cooked with an autoclave digester by chemical extraction using alkali solution (Sodium hydroxide-ethanol solution) in an amount proportionate to the fibers to be cooked (usually 60/40 V/V). The cooked fragments then soften thereby removing fats and other elements. Those fragments are thoroughly washed and physically hammered slowly not to damage the fibers. Fibers are then separated from cellulose and lignin with pressure after oven drying.

These bamboo fibers were produced in accordance with the standard aspect ratio. Bamboo fibers in this specific research were examined to have a length and diameter in the ranges of (3-5) cm and (0.5-1.0) mm after measuring representative samples with help of rulers. Therefore, the aspect ratio varies from 30-100 accordingly. General Bamboo fiber extraction processes from bamboo plant are discussed below.

- ◊ A 3.5 years old bamboo plants having 4.5m average length were collected. Bamboo culms were prepared through cutting the internodes into 5cm culm lengths using power saw. Nodes were excluded because of its difficulty in extracting fiber from it. Figure 3.1 below shows electrical aided power saw and the bamboo culm cut into desirable pieces.

a) b)

Figure 3.1: a) power saw, b) Bamboo culm cut into desirable pieces

- ◊ Bamboo culms were splitted into smaller sized bundles by mechanical hammering in order to prepare the sample for pulping.
- ◊ These smaller sized fragments were made ready to be pulped with the help of chemicals and digested in an autoclave digester. Chemicals used were Soda-ethanol pulping liquor prepared from sodium hydroxide solution and ethanol water.
- ◊ In co-operation with school of Chemical and Bio Engineering laboratory, autoclave digester was setup for the pulped sample to be cooked as shown in Figure 3.2 below. The temperature and pressure for this specific pulp was adjusted to be 150^{o}C and 20kPa/cm^{2}, respectively, on the controller. One term autoclave digestion lasted 45minutes and waited for 30minutes for cooling the autoclave down.

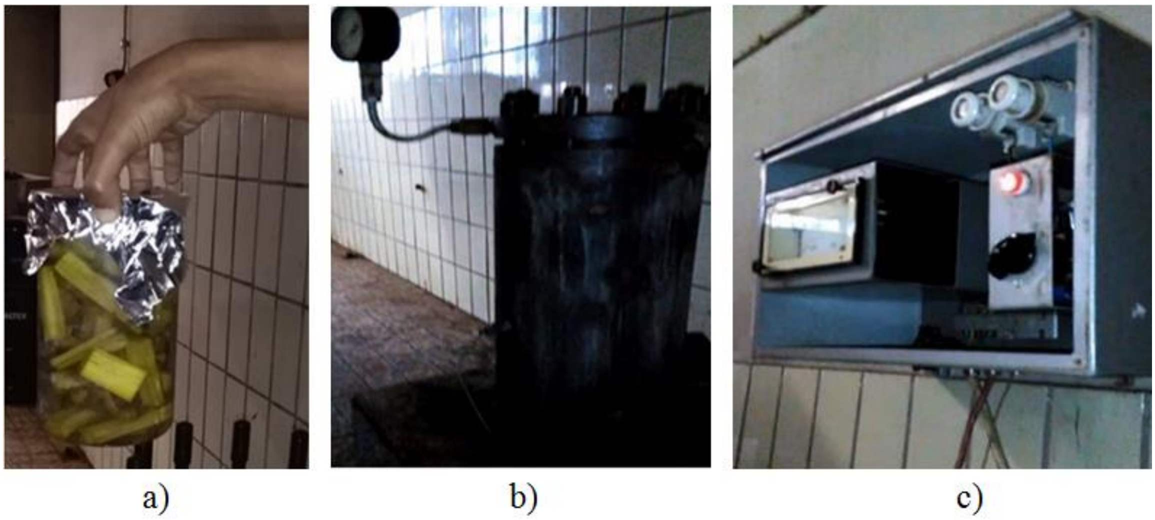

Figure 3.2: a) Pulped bamboo, b) Autoclave digester and c) Controller

- ◊ The pulped bamboo culms were then removed from the autoclave digester and washed thoroughly with water to clean the chemical from its surface. This pulp was then hammered mechanically to separate fiber and lignin. Mechanical hammering could not fully separate the lignin and fiber and hence sample was dried in an oven. The final bamboo fibers are separated from the oven dried samples by rubbing with pressure. Figure 3.3 below shows the slightly hammered fiber with lignin, fibers and lignin separated after oven drying.

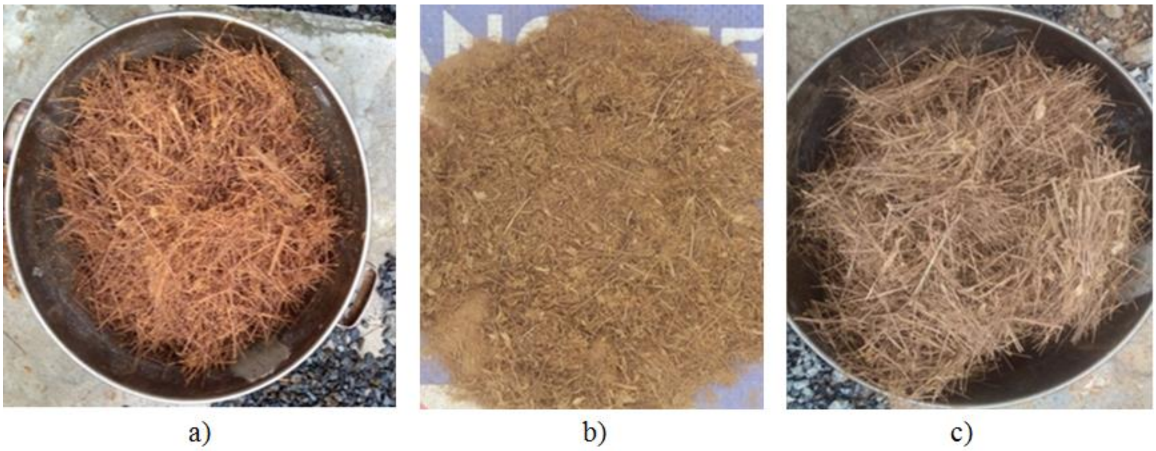

Figure 3.3: a) Fiber with lignin, b) lignin after oven dry and c) Fibers separated

3.3.2 Testing constituent materials

Aggregate needs to be standardized because concrete strength and quality depends on physical properties, mechanical properties and chemical composition of the parent aggregate making materials. All physical tests conducted for both fine and coarse aggregates are discussed in the following sessions.

3.2.2.1 Tests for coarse aggregates

In this specific research, basaltic crushed rock aggregates having nominal maximum size of 19mm were made use of through blending in order to keep gradation in the range specified on Ethiopian Standard. Physical property tests; like gradation, specific gravity, water absorption, moisture content and unit weight of the aggregates were conducted.

i. <u>Sieve analysis</u>

Sieve analysis is a procedure for the determination of the particle size distribution of aggregates using a series of square or round openings sieves starting with the largest opening at the top. According to the Ethiopian Standard coarse aggregates are those between 75 and 4.75 mm in size. Samples were prepared for particle size distribution in such a way that crushed basaltic stones with 19mm nominal maximum sizes were blended to keep gradation requirement within the range specified on Ethiopian Standard for grading coarse aggregates. The fineness modulus for this coarse aggregate sample was found to be 2.02%.

Figure 3.4 below shows gradation curve for coarse aggregate used in the research in comparison to the minimum and maximum quantities of coarse aggregates on each series of sieves specified in the Ethiopian Standard (ES C.D3.201. The detail gradation test for coarse aggregates are given in Appendix C (C1) of this paper.

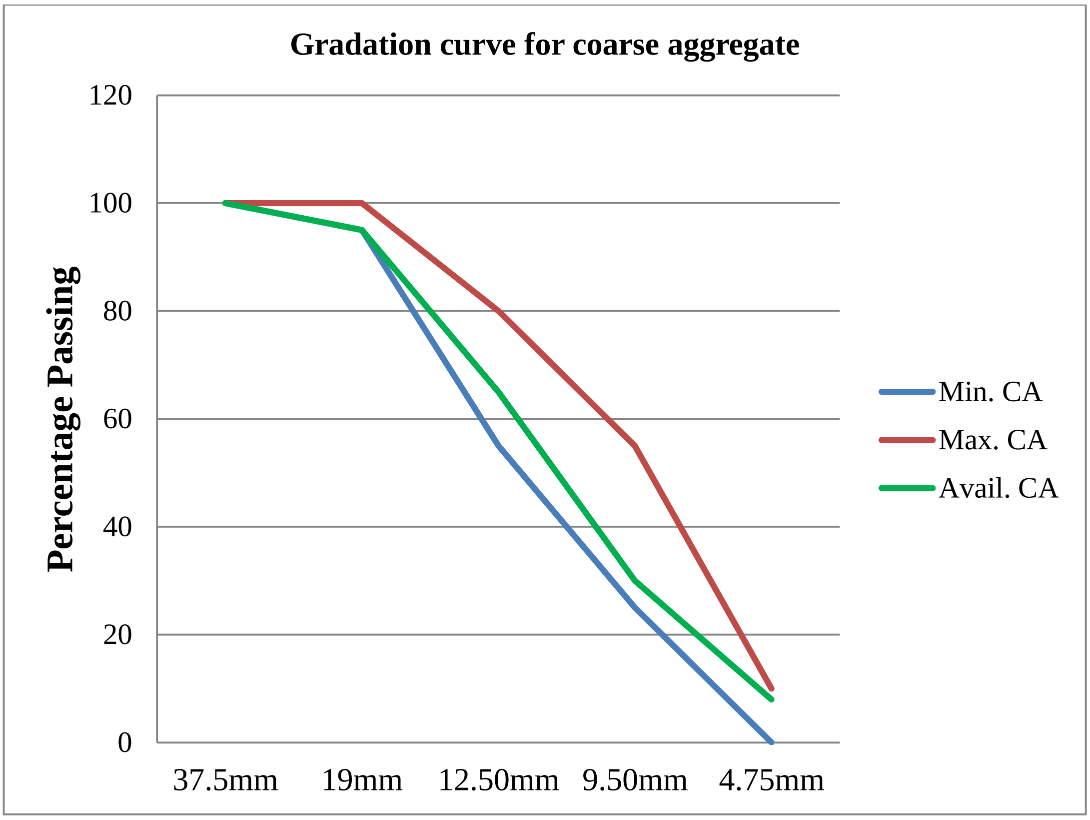

Figure 3.4: Gradation curve for coarse aggregate

ii. Specific gravity and absorption capacity

Specific gravity is the ratio of the density of a substance to the density of a reference substance usually water; equivalently, it is the ratio of the mass of a substance to the mass of water for the same given volume. Absorption is the process by which water is drawn into and tends to fill the permeable pores in a porous solid body.

An approximate coarse aggregate sample of 5kg was acquired, by using quartering from the mass sample. All aggregate materials passing No. 4 (4.75 mm) sieve were rejected.

Measured quantities:

A = 4936 g

B = 5027 g

C = 3230 g

Where:

A = weight of oven-dry sample in air, [g]

B = weight of saturated – surface – dry sample in air, [g]

C = weight of saturated sample in water, [g]

Table 3.1 shown below summarizes the test results for bulk specific gravity, bulk specific gravity (SSD basis), apparent specific gravity and absorption capacity of coarse aggregates.

Table 3.1: Specific Gravities and Absorption Capacity of Coarse aggregate

	Bulk specific gravity	**Bulk specific gravity (SSD basis)**	**Apparent specific gravity**	**Absorption capacity**
Calculations	$\frac{A}{B-C}$	$\frac{B}{B-C}$	$\frac{A}{A-C}$	$\frac{B-A}{A} * 100$
Results	2.76	2.80	2.89	1.84%

iii. <u>Moisture content of coarse aggregates:</u>

Moisture content of coarse aggregate samples has to be determined as it affects workability and water-cement ratio in the mix design. A design water-cement ratio is usually specified based on the assumption that aggregates are inert (neither absorb nor give water to the mixture) and hence aggregates from different sources do not comply with this assumption of water cement ratio.

To determine moisture content, 2 kg coarse aggregate sample was weighed and oven dried for about 24hrs at a temperature of 105^{o}C-110^{o}C. The sample was then removed from the oven and placed on a desiccator for about an hour in order to cool without absorbing water from the atmosphere. The sample was then weighed (oven dry weight). Moisture content of the coarse aggregate in this case was calculated to be 2.04%. Detailed moisture content determinations for coarse aggregates are discussed in Appendix C (C1) of this paper.

iv. <u>Unit weight of coarse aggregates</u>

The unit weight measures the volume that the graded aggregate will occupy in concrete and includes both the solid aggregate particles and the voids between them. The unit weight is simply measured by filling a container of known volume and weighing it. Oven-dried coarse aggregate samples were used in this specific test.

In determining unit weight of coarse aggregate, rodding procedure was followed where it is applicable to the aggregates of 40 mm maximum size [32]. Normal crushed rocks and gravels have bulk unit weight of 1520-1680kg/m^3 and produce normal weight concrete. Table 3.2 below shows dry rodded unit weight calculation of coarse aggregate used in this specific research.

Table 3.2: Unit weight determination for coarse aggregate

	Weight of container (kg)	**Weight of sample & measure (kg)**	**Inside diameter of measure (mm)**	**Inside height of measure (mm)**	**Volume of measure (m^3)**	**Unit weight of coarse aggregate. (kg/m^3)**
Calc.	-	-	-	-	$V = \frac{\pi D^2 h}{4}$	$\frac{28054 - 4841}{0.01382}$
Results	4841	28054	253	275	0.01382	**1679.67**

3.2.2.2 Tests for fine aggregates

i. <u>Silt content</u>

The distinction between silt & clay can't be based on particle size because both are microscopic having sizes finer than No. 200 (0.075mm) sieve and hence the significant physical properties of the two materials are related only indirectly to the size of particles. The objective of this test is to determine these fine particle contents from the mass sand sample.

<u>Test results:</u>

A = 10ml

B = 290ml

Where:

A = amount of silt deposited above the sand

B = amount of clean sand

<u>Calculation:</u>

$$\text{Silt content (\%)} = \frac{\text{A}}{\text{B}} * 100$$

$$\text{Silt Content (\%)} = \frac{10}{290} \text{ X } 100 = 3.45 < 6 \text{ ..... OK!}$$

According to the Ethiopian Standard, if the silt content of the sand is more than 6% it is recommended either to wash or to reject the sand. The sand samples in this specific research were used without washing since silt content is less than 6%.

ii. Sieve analysis

According to the Ethiopian Standard, fine aggregates are those between 9.50mm and 150 μm in size. Samples were prepared for particle size distribution in such a way that river sand with 4.75 mm nominal maximum sizes was prepared in accordance with the gradation requirement specified in the Ethiopian Standard for the grading of fine aggregates. Fineness modulus for this fine aggregate sample came to be 2.60%. The sand sample used in this specific research was tested to have a particle size distribution within the range of the Ethiopian Standard for the grading of fine aggregate. Thus it satisfies the gradation requirement.

A detailed gradation test results for fine aggregates in comparison with the requirements set in the Ethiopian Standard for grading of fine aggregate (ES C.D3.201) using ranges of percentage passing through each sieve openings were presented by Appendix C (C2) of this paper. Figure 3.5 below shows gradation curve for fine aggregate used in the research in comparison to the minimum and maximum quantities of fine aggregates on series of sieves specified in the Ethiopian Standard.

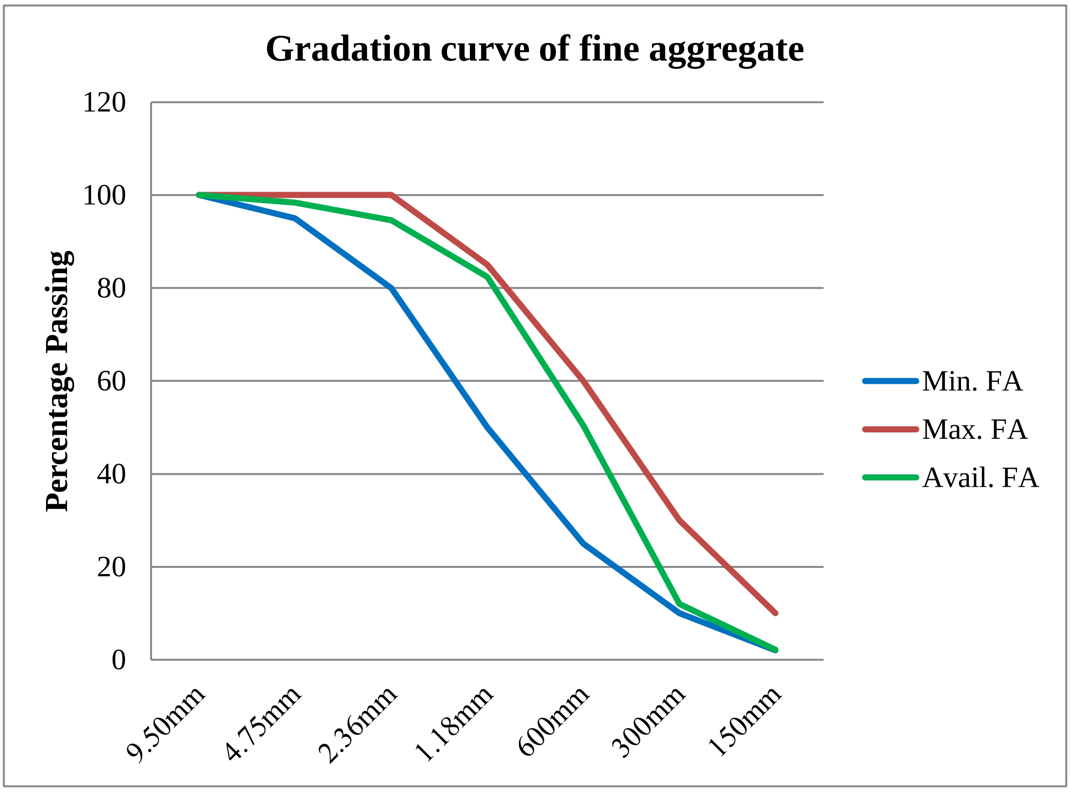

Figure 3.5: Gradation curve for fine aggregate

iii. Specific gravity and absorption capacity

The objective of this test is to determine bulk and apparent specific gravity, and absorption capacity of the fine aggregates.

Approximately 500g of the fine aggregate sample from the availed mass of the total was taken by using a method of sample splitter. Sample tests were prepared and the procedures were followed in accordance with the guide of Construction Materials Laboratory Manual by Abebe Dinku.

Measured quantities:

Weight of the sample = 500g

W = 320g

V = 975.39 ml

Va =769.80 ml

A = 475 g

Where,

W = weight of pycnometer, gm.

V = volume of flask/container

Va = volume of water added to pycnometer [cm^3]

A = weight of oven dry sample in air [g]

Calculation:

C = 0.9976Va + 500 +W

= 0.9976*(769.80) + 500 + 320

= 1587.95g

B = 0.9976V + W

= 0.9976*(975.39) + 320

= 1293.05g

Where, C = weight of pycnometer filled with sample plus water, [gm]

B = weight of flask filled with water, [gm]

Table 3.3 shown below summarizes the test results for bulk specific gravity, bulk specific gravity (SSD basis), apparent specific gravity and absorption capacity of fine aggregates.

Table 3.3: Specific gravities and absorption capacity of fine aggregate

	Bulk specific gravity	**Bulk specific gravity (SSD basis)**	**Apparent specific gravity**	**Absorption capacity**
Calculations	$\frac{A}{B+500-C}$	$\frac{500}{B+500-C}$	$\frac{A}{B+A-C}$	$\frac{500-A}{A}x100$
Results	2.32	2.44	2.64	5.26%

iv. <u>Moisture content</u>

To determine the moisture content, 500g fine aggregate sample was weighed and oven dried for about 24hrs to remove moisture contained in the sample with a temperature of 105^{o}C-110^{o}C. The sample was then removed from the oven and placed on a desiccator for about an hour in order to cool without absorbing water from the atmosphere. The sample was then weighed (oven dry weight). Moisture content of the fine aggregate in this specific research was calculated to be 3.10%. A detailed moisture content determination for fine aggregates is discussed in Appendix C (C2) of this paper.

3.3.3 Mix proportions

The objective of concrete mix proportioning is to determine the most economical and practical combination of readily available materials that will satisfy the performance requirement under a particular condition of use.

Concrete mix proportions are usually expressed on the basis of mass of ingredients per unit volume. Proportioning of concrete by absolute volume method involves calculating the volume of each ingredient and its contributions to make 1m^3 of concrete. Volumes are subsequently converted to design weights. These conversions to weights are accomplished by taking the known volumes of ingredients and multiplying by the specific gravity of ingredients and again multiplying by the density of water.

In this specific research mix design of bamboo fiber reinforced concrete with determined ratios of cement, sand, water, coarse aggregate and bamboo fiber were proportioned for C25 concrete grade based on DOE mix design method. The completed mix design table with DOE mix design procedure is shown in Appendix A of this paper. The wet density of 1m^3 of concrete from DOE mix design method was determined to be 2400Kg/m^3. Table 3.5 below shows weights of ingredients required to make 1m^3 of concrete for each percentage additions of bamboo fiber by weight of concrete namely 0%, 0.10%, 0.20% and 0.30%.

Table 3.4: Quantities of materials for each mix in kg for 1m^3 concrete

Mix code	**Bamboo fiber (%)**	**w/c ratio**	**For 1m^3 of concrete**					
			Cement (kg)	**Water (kg)**	**Sand (kg)**	**Coarse Agg. (kg)**	**Bamboo fiber (kg)**
M_0	0.00%	0.59	325	202.7	685	1192.4	0.00
M_1	0.10%	0.59	325	202.7	685	1192.4	2.40
M_2	0.20%	0.59	325	202.7	685	1192.4	4.80
M_3	0.30%	0.59	325	202.7	685	1192.4	7.20

3.3.4 Mixing and casting

Mixing of concrete is made in the laboratory either with hand or machine mixer based on ASTM C192 standard. The mixing time of freshly mixed concrete takes about 8 minutes and half seconds under a controlled room temperature and humidity. Concrete ingredients are tested, supplied separately and mixed using a machine mixer in this specific research.

Cube samples of size 100mm, cylindrical samples of size 150mm diameter and 300mm height and prismatic beam samples of size 100mm x 100mm x 500mm for testing compressive strength, tensile strength and flexural strength; respectively, were casted.

Three 100mm cube samples for each percentage addition of bamboo fiber by weight of concrete (0%, 0.10%, 0.20%, and 0.30%); 24 cubes in total for 7th and 28th day Compressive Strength testing were casted.

Three cylindrical samples each for percentage addition of bamboo fiber by weight of concrete (0%, 0.10%, 0.20%, and 0.30%); 24 cylinders in total for 7th and 28th day Split Tensile Strength testing were casted.

Two prismatic (beam) samples each for percentage addition of bamboo fiber by weight of concrete (0%, 0.10%, 0.20%, and 0.30%); 16 beams in total for 7th and 28th day Flexural Strength testing were casted. Figure 3.6 below shows cube samples, cylindrical samples and prismatic samples casted for testing.

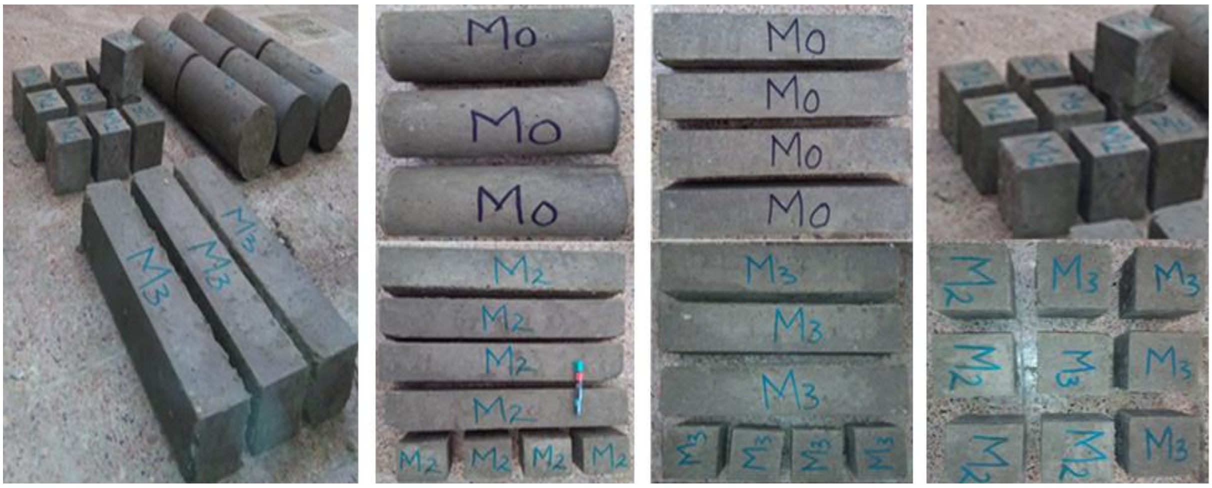

Figure 3.6: Cube, prism and cylindrical samples casted for testing

3.3.5 Curing

The casted specimens were demoulded after 24hrs of casting and cured with ponding according to ASTM C 192/C 192M till respective dates of testing. Curing is designed primarily to keep concrete moist, by preventing loss of moisture from the concrete during which it is gaining its strength.

3.3.6 Testing

Out of the many tests applied to concrete, compressive strength test is the utmost important which gives an idea about all the characteristics of concrete. Test for compressive strength is carried out either on cube or cylinder specimens. Various standard codes recommend concrete cylinder or concrete cube as the standard specimen for the test. American Society for Testing and Materials ASTM C39/C39M provides Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, for cube test two types of specimens either cubes of 15cm X 15cm X 15cm or 10cm X 10cm x 10cm depending upon the size of aggregate are used. In this specific research cubes of 10cm x 10cm x 10cm sizes were preferred due to materials scarcity. These specimens were tested with a compression testing machine after 7 days curing and 28 days curing. The Load was applied gradually at the rate of 140 kg/cm^2 per minute till the specimens fail. Load at failure divided by area of specimen gives the compressive strength of concrete.

Flexural strength is one measure of the tensile strength of concrete. It is a measure of an amount of stress or force that a beam or slab can withstand from bending failures. The flexural strength is expressed as Modulus of Rupture in (MPa) and is determined by standard test methods ASTM C 78 (third-point loading) or ASTM C 293 (center-point loading). Beam samples having 10cm x 10cm x 50cm sizes were tested after 7 days and 28 days of curing according to ASTM C 78 (third-point loading) standard test methods in this specific research.

Splitting tensile strength test on concrete cylinder is a method to determine the tensile strength of concrete. The concrete is very weak in tension due to its brittle nature and is not expected to resist the direct tension. The concrete develops cracks when subjected to tensile forces. Thus, it is necessary to determine the tensile strength of concrete through finding the load at which the concrete members may crack. Split tensile strength of cylindrical samples having 30cm height and 15cm diameter were tested after 7 days or 28 days of curing in accordance with ASTM C496 standard testing methods.

4. Test Results and Discussions

This specific part presents test results for split tensile strength, flexural strength and compressive strength of bamboo fiber reinforced concrete as well as plain concrete.

4.1 Test results

4.1.1 Split tensile strength test

The splitting tensile strength test is an indirect tension test for concrete. It is carried out on a standard cylindrical specimen, tested on its side in diametric compression. In split tensile strength testing, four different percentage addition of bamboo fiber by weight of concrete namely; 0%, 0.1%, 0.2% and 0.3% were undertaken. Three cylindrical samples were tested for each percentage addition of bamboo fiber. Typical failure loads and tensile strength of 28th day BFRC under tensile loading were presented in the Table 4.1 as shown below. A detailed test results of split tensile strength at the age of 7th and 28th for bamboo fiber reinforced concrete are presented in appendix C2 at the end this document.

Table 4.1: 28th day split tensile strength test results

Mix-code	Sample no.	Failure load (kN)	Splitting Tensile Strength(MPa)
M_0	1	160.2	2.266
	2	158.6	2.243
	3	149.4	2.113
	Mean	**156.06**	**2.207**
M_1	1	131.1	1.856
	2	188.7	2.671
	3	169.9	2.405
	Mean	**163.23**	**2.311**
M_2	1	170.9	2.419
	2	146.6	2.075
	3	152.9	2.164
	Mean	**156.80**	**2.219**
M_3	1	123.4	1.747
	2	124.1	1.757
	3	137.8	1.950
	Mean	**128.43**	**1.818**

4.1.2 Flexural strength test

Flexural strength test gives another way for estimating tensile strength of concrete. During pure bending the member resisting the action is subjected to internal stresses (shear, tensile and compressive). For a bending force applied downward for a member simply supported at its two ends, fibers above the neutral axis are generally subjected to compressive stresses and those below the neutral axis undergo tensile stresses. For this load and support system, portions of the member near the supports are subjected to relatively higher shear stresses than tensile stresses. For the sake of testing two prismatic samples each for percentage addition of bamboo fiber by weight of concrete namely; 0%, 0.1%, 0.2% and 0.3% were tested with third-point loading in accordance with ASTM C78 standard. Typical failure loads and bending strength of 28th day BFRC samples under third-point loading are presented in the Table 4.2 as shown below. A detailed test results of flexural strength at the age of 7th and 28th for bamboo fiber reinforced concrete are presented in Appendix C3 at the end this document.

Table 4.2: 28th day flexural strength test results

Mix-code	Sample no.	Failure load (kN)	Bending Strength (MPa)
M_0	1	7.406	6.665
	2	7.330	6.597
	Mean	**7.368**	**6.631**
M_1	1	7.487	6.738
	2	7.774	6.997
	Mean	**7.630**	**6.8675**
M_2	1	7.181	6.463
	2	8.268	7.441
	Mean	**7.724**	**6.952**
M_3	1	8.121	7.309
	2	7.612	6.851
	Mean	**7.866**	**7.080**

4.1.3 Compressive strength test

Three 100mm sized cube samples were tested for each percentage addition of bamboo fiber in this specific thesis. In the UK, BS 8500 states that the compressive strength of 150mm cubes and 100mm cubes are considered equivalent. Neville, Properties of concrete 4th edition, reports that a 150mm cube is 96% the strength of a 100mm cube. A correction factor is not used in the European Standard and 100, 150 or 200mm cubes can be used without correction to the compressive strength obtained from the test when checking for strength class conformity. Typical failure loads and compressive strength of BFRC by the 28th day of 100mm cube samples are presented in the Table 4.3 as shown below. Compressive strength of 100mm cube samples are converted to compressive strength of 10mm cubes by multiplying it with a factor 0.96 as stated in Neville. A detailed test results of compressive strength at the age of 7th and 28th for bamboo fiber reinforced concrete are presented in Appendix C1 at the end this document.

Table 4.3: 28th day compressive strength test results

Mix-code	Sample No.	Failure load of 100mm cubes (kN)	Compressive Strength of 100mm cubes, (MPa)	Compressive Strength of 150mm cubes, (MPa)
M_0	1	253.3	25.33	24.3168
	2	265.2	26.52	25.4592
	3	266.9	26.69	25.6224
	Mean	**261.80**	**26.18**	**25.1328**
M_1	1	341.9	34.19	32.8224
	2	349.2	34.92	33.5232
	3	334.5	33.45	32.1120
	Mean	**341.86**	**34.18**	**32.8192**
M_2	1	330.2	33.02	31.6992
	2	297.4	29.74	28.5504
	3	294.0	29.4	28.2240
	Mean	**307.20**	**30.72**	**29.4912**
M_3	1	255.8	25.58	24.5568
	2	256.5	25.65	24.6240
	3	250.2	25.02	24.0192
	Mean	**254.16**	**25.42**	**24.4000**

4.1.4 Fresh concrete properties

Among the fresh concrete properties slump test and fresh concrete density tests are investigated for each concrete mixture incorporating 0.00%, 0.10%, 0.20% and 0.30% addition of bamboo fiber by weight of concrete. Table 4.4 below shows slump and fresh concrete densities for each mix.

Table 4.4: Slump and fresh concrete density test results

Mix-code	Slump (mm)	Fresh concrete density (kg/m^3)
M_0	60	2409.7
M_1	35	2386.1
M_2	35	2382.0
M_3	30	2366.6

Slump results for mixes M1 and M2 in the table above are reduced by 41.67% and 50% for mix M3. Slump results of all the mixes presented in the above table complies with the slump ranges originally assumed in the mix design i.e. (30-60mm) and hence do not cause workability problem with the amount of bamboo fiber used in the experiment.

Fresh concrete density for mix M1 (mix with 0.1% bamboo fiber) was reduced by 0.98%, mix M2 (mix with 0.2% bamboo fiber) reduced by 1.15% and mix M3 (mix with 0.3% bamboo fiber) was reduced by 1.79% compared to a reference plain concrete.

Balling effect during the mix happened due to high volume percentages of bamboo fiber addition size and quality of coarse aggregate, water-cement ratio and method of mixing. Balling effect in bamboo fiber reinforced concrete occurred in mixes M_2 and M_3. Most fiber balling occurs during the fiber addition process and this can be eliminated by care in the sequence and rate of fiber addition.

Eventhough slump test reveals that all mixes are workable, increases in aspect ratio, volume percentage of fibers, size and quantity of coarse aggregates intensified balling tendencies. Friction between fibers and aggregates controls fiber orientation and distribution.

4.2 Discussions

4.2.1 Variability of test results

A strength test result is defined as the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete. A strength test cannot be based on only one test specimen; a minimum of two test samples are required for each test. Testing two or three samples preserves the confidence level of the average strength.

Concrete tests for strength are typically treated as if they fall into a distribution pattern similar to the normal frequency distribution curve. As variation in strength results increases, the spread in the data increases and the normal distribution curve becomes lower and wider. The normal distribution can be fully defined mathematically by statistical parameters like mean, standard deviation and coefficient of variation.

Mean: is the average strength tests results.

Standard deviation: is the most generally recognized measure of dispersion of the individual test data from their average.

Coefficient of variation: the sample standard deviation expressed as a percentage of the average strength is called the coefficient of variation.

Table 4.5 below shows values of Mean, Standard deviation and Coefficient of variation calculated for a set of cylindrical specimens casted for split tensile strength test.

Table 4.5: Values of statistical parameters in split tensile testing

Mix-code	Sample No.	Split tensile strength, (MPa)	Mean strength, (MPa)	Standard deviation, (S)	Coefficient of variation, (V)
M_0	1	2.266	2.207	0.067	3.05%
	2	2.243			
	3	2.113			
M_1	1	1.856	2.311	0.339	14.68%
	2	2.671			
	3	2.405			
M_2	1	2.419	2.219	0.146	6.56%
	2	2.075			
	3	2.164			
M_3	1	1.747	1.818	0.093	5.13%
	2	1.757			
	3	1.950			

Table 4.6 below shows values of Mean, Standard deviation and Coefficient of variation calculated for a set of prismatic (beam) specimens casted for flexural strength test.

Table 4.6: Values of statistical parameters in flexural strength testing

Mix-code	Sample No.	Flexural strength, (MPa)	Mean strength, (MPa)	Standard deviation, (S)	Coefficient of variation, (V)
M_0	1	6.665	6.631	0.034	0.512%
	2	6.597			
M_1	1	6.738	6.867	0.129	1.885%
	2	6.997			
M_2	1	6.463	6.952	0.489	7.034%
	2	7.441			
M_3	1	7.309	7.080	0.229	3.234%
	2	6.851			

Table 4.7 below shows values of Mean, Standard deviation and Coefficient of variation calculated for a set of cubical specimens casted for compressive strength test.

Table 4.7: Values of statistical parameters in compressive strength testing

Mix code	Sample No.	150mm cube comp. strength, (MPa)	Mean comp. strength, (MPa)	Standard deviation, (S)	Coefficient of variation, (V)
M_0	1	24.3168	25.1328	0.5808	0.0231%
	2	25.4592			
	3	25.6224			
M_1	1	32.8224	32.8192	0.5761	0.0175%
	2	33.5232			
	3	32.1120			
M_2	1	31.6992	29.4912	1.5670	0.0531%
	2	28.5504			
	3	28.2240			
M_3	1	24.5568	24.4000	0.2706	0.0111%
	2	24.6240			
	3	24.0192			

A single strength test result of a concrete mixture, however, does not provide sufficient data for statistical analysis. As with any statistical estimator, the confidence in the estimate is a function of the number of test results. According to ACI 214R-02 within-test standard deviation is estimated from the average range of at least 10, and preferably more, strength test results of a concrete mixture, tested at the same age. Eventhough within test variability requires more data, it is desired to check the variations of strength test results with the help of statistical parameters and hence analysis with the help of coefficient of variations using two beams, three cubes and three cylinders for each mixes were made.

From the calculated results of statistical parameters, especially, coefficient of variations presented in the above tables (Table 4.5, Table 4.6 and Table 4.7) are within test variability ranges of ACI 214R-02 for strength test data; which are discussed below.

Within test variability of split tensile strength tests for mix M_0 lies in a very good range (3% < CoV < 4%) whereas within test variability lies in poor range (CoV > 6%) for M_1 and M_2 and lies in fair range (5% < CoV < 6%) for M_3.

Within test variability of flexural strength tests for mixes M_0 and M_1 lies in an excellent range whereas within test variability lies in poor range (CoV > 6%) for M_2 and very good range (3% < CoV < 4%) for M_3.

Within test variability of compressive strength tests are in an excellent range where coefficient of variation is less than 3% according to ACI 214R-02.

Most of the within test variability ranges are from excellent to fair for all the strength test results in this specific research. But some of the strength test results fails to comply with the requirement of ACI 214R-02. These invariability (within test variability of poor range) occurs due to different reasons; some of these are lack of having similar sample molds, faulty test procedures like in the case applying line loads for split tensile strength testing, variations of ingredients due to techniques of batching, mixing and sampling and etc.

4.2.2 Discussion on splitting tensile strength

Mean splitting tensile strength of BFRC with 0.10% addition of bamboo fiber by weight of concrete have showed an increment by 4.7% compared to plain concrete. BFRC with 0.20% bamboo fiber have also showed tensile strength increment of 0.54% which is almost insignificant. BFRC with 0.30% bamboo fiber have showed a strength reduction of 17.6%. The mean failure loads with 0.1% and 0.2% bamboo fiber were also increased by 4.6% and 0.47%; respectively, compared to failure load of a plain concrete. But the mean failure loads with 0.3% bamboo fiber were reduced by 17.7% compared to a plain concrete. The 28th day mean splitting tensile strength test results for various ratios of bamboo fiber addition by weight of concrete were compared with a plain concrete as shown in the figure 4.1 below.

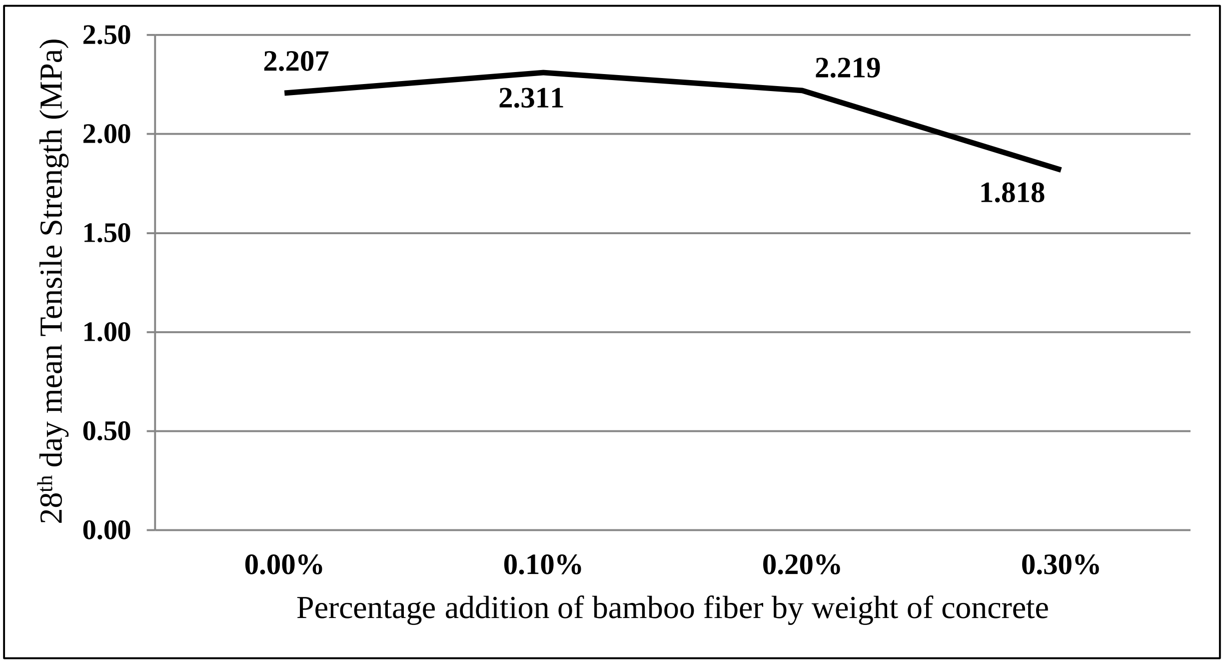

Figure 4.1: Tensile strength chart for each percentages of bamboo fiber addition

4.2.3 Discussion on flexural strength

Mean flexural strength of BFRC with 0.10% addition of bamboo fiber by weight of concrete has showed an increment of 3.57% compared to plain concrete. BFRC with 0.20% bamboo fiber addition have also showed a bending strength increment of 4.84%. BFRC with 0.30% bamboo fiber have showed a bending strength increment of 6.77%. The mean failure loads with 0.1%, 0.2% and 0.3% bamboo fiber were also increased by 3.55%, 4.83% and 6.75%; respectively, compared to the failure load of a plain concrete. The 28th day mean flexural strength test results for various ratios of bamboo fiber addition by weight of concrete were compared with a plain concrete as shown in the figure 4.2 below.

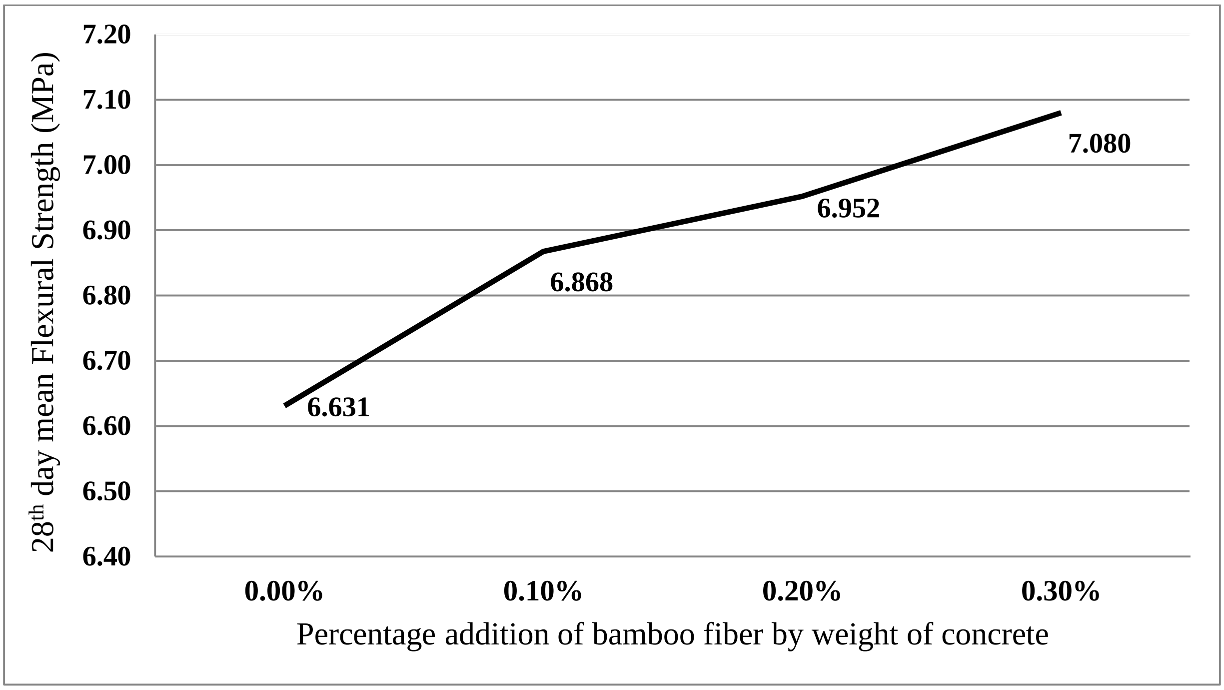

Figure 4.2: Flexural strength chart for each percentages of bamboo fiber addition

4.2.4 Discussion on compressive strength

Mean compressive strength of BFRC with 0.10% addition of bamboo fiber by weight of concrete have showed an increment of 30.58% compared to plain concrete. BFRC with 0.20% bamboo fiber have also showed tensile strength increment of 17.34%. BFRC with 0.30% bamboo fiber have showed a compressive strength reduction of 2.92%. The mean failure loads with 0.1% and 0.2% bamboo fiber were also increased by 30.58% and 17.34%; respectively, compared to the failure load of a plain concrete. But the mean failure loads with 0.3% bamboo fiber were reduced by 2.92% compared to a plain concrete. The 28th day mean compressive strength test results for various ratios of bamboo fiber addition by weight of concrete are compared with a plain concrete as shown in the figure 4.3 below.

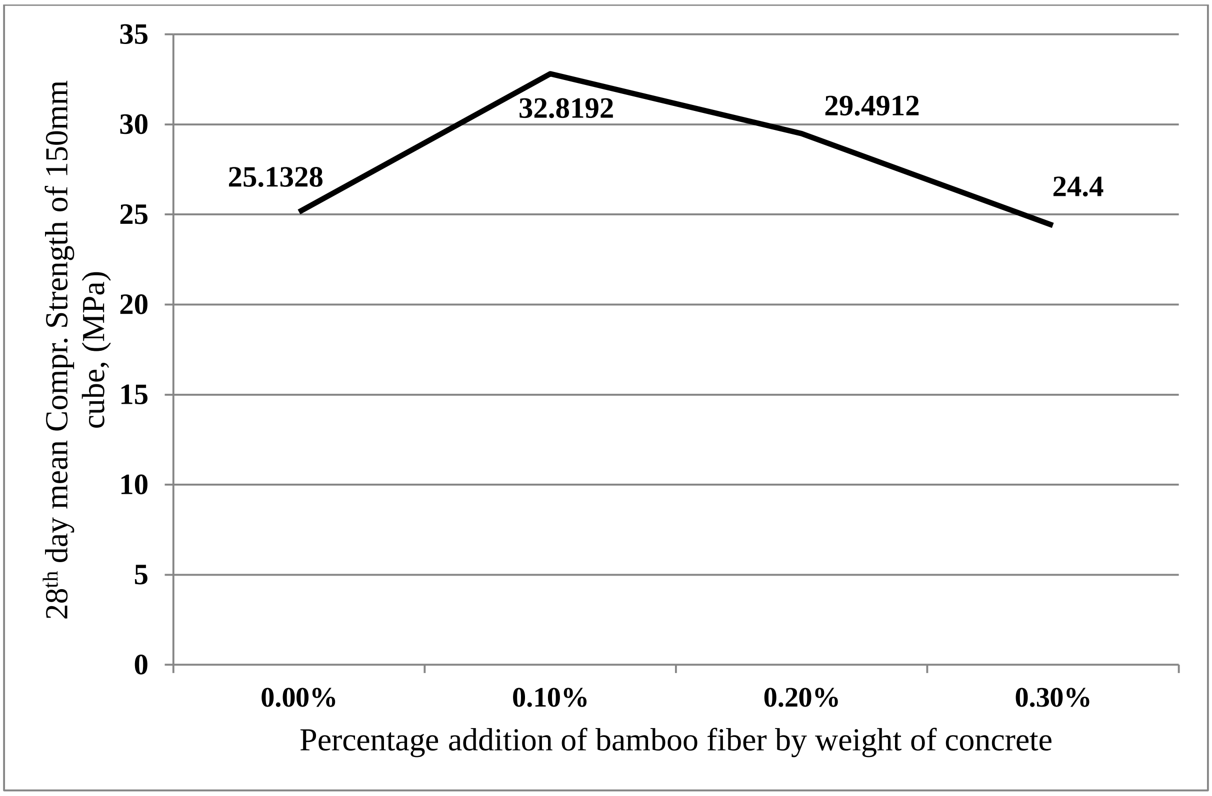

Figure 4.3: Compressive strength chart for each percentages of bamboo fiber addition

Comparison between bamboo fibers reinforced concrete and reference plain concrete with regard to the strength parameters of hardened concrete; namely, split tensile strength, flexural strength and compressive strength are discussed above. The following paragraphs are general discussions and interrelations forwarded on the values of strength tests.

As discussed in above in figure 4.1, split tensile strength of bamboo fiber reinforced concrete with 0.1% and 0.2% bamboo fiber addition showed an increment while bamboo fiber addition of 0.3% reduced the tensile strength of concrete.

As of figure 4.2, flexural strength of bamboo fiber reinforced concrete with 0.1%, 0.2% and 0.3% bamboo fiber addition showed flexural strength increment.

As shown in figure 4.3 above, compressive strength of bamboo fiber reinforced concrete with 0.1% and 0.2% bamboo fiber addition showed an increment while bamboo fiber addition of 0.3% reduced compressive strength of concrete.

The flexural strength of concrete would be the same as the tensile strength if the material were homogeneous. If the same material was subjected to only tensile forces, then all the fibers in the material are at the same stress and failure will initiate when the weakest fiber reaches its limiting tensile stress. Therefore, it is common for flexural strengths to be higher than tensile strengths for the same material.

For 0.3% bamboo fiber addition split tensile strength of BFRC was reduced in contrary to the flexural strength of BFRC with the same percentage of bamboo fiber addition. This contrary in strength variation between split tensile strength and flexural strength might have happened due to the following combinations of factors; defect in materials and moulds that affect testing procedures, inconsistent and non-uniform concrete mix and unevenly distribution of fibers. Results from the split cylinder tensile strength test (ASTM C 496) for FRC specimens are difficult to interpret after the first matrix cracking and should not be used beyond first crack because of unknown stress distributions after first crack. But, flexural strength test of FRC specimens are interpreted after the first cracks are developed because of fibers acting toward cracks propagation.

5. Conclusions and Recommendations

Based on the experimental program conducted on mechanical properties of bamboo fiber reinforced concrete (BFRC) regarding laboratory investigations of slump test, fresh density, compressive strength, flexural strength and split tensile strength; conclusions are drawn and recommendations are forwarded on the effect of bamboo fiber addition in concrete.

5.1 Conclusions

1. There is a significant increase of mean split tensile strength of a bamboo fiber reinforced concrete of 4.70% by 28th day at 0.1% bamboo fiber addition. The split tensile strength of BFRC with 0.20% bamboo fiber has showed an increment of 0.54% which is almost insignificant compared to a plain concrete. Higher percentage addition of bamboo fiber has not improved the split tensile strength as in the case of 0.3%; which showed a reduced tensile strength result compared to the plain concrete.
2. The 28th day test results of BFRC incorporating 0.1%, 0.2% and 0.3% bamboo fiber showed flexural strength increment of standard prisms by 6.868%, 6.952% and 7.080%; respectively, compared to the reference plain concrete.
3. Compressive strengths with 0.1% and 0.2% addition of bamboo fiber by weight of concrete were increased by 30.58% and 17.34%; respectively, compared to a plain concrete; while 0.3% bamboo fiber addition has reduced the compressive strength by about 2.92%, as compared to the reference plain concrete.
4. Among the three bamboo fiber additions under investigation, 0.10% bamboo fiber addition by weight of concrete showed a maximum strength increment in Split tensile strength and Compressive strength.
5. Slump test of a concrete mixes with 0.1% and 0.2% bamboo fibers addition showed reduction by 41.67%; at a constant water cement ratio and mixes with 0.3% bamboo fibers showed a slump reduction of 50% compared to the reference plain concrete.
6. The slump values for the three mixes are yet within the acceptable range and workable according to the assumption from DOE mix design. Fresh concrete density for BFRC with 0.1%, 0.2% and 0.3% bamboo fiber showed reductions of 0.98%, 1.15% and 1.79%; respectively, compared to the reference plain concrete. These reductions are not significant and are due to the lesser specific gravity of the bamboo fiber used as reinforcement.

5.2 Recommendations

1. It is highly recommended for the construction companies involved in the current construction industry to be very familiar in supporting different researches and adopt the use of fibers especially natural fibers which are more economical and eco-friendly than the other fibers for an improved concrete strength production.
2. Government officials, professional association, practitioners and universities have to work together to prepare guide line; and necessary documents, update standards, enforce regulations, promote natural fiber reinforced concrete production, and push for a better technology to introduce a concrete of improved strength in the Ethiopian construction industry.
3. Primarily, conventional bamboo fiber extraction techniques do have problems; be it in quality, accuracy and efficiency. To solve these problems, it is strongly recommended to develop a new method of obtaining bamboo fibers with mechanical machines that extract and prepares bamboo fibers with a desired quality, accuracy and efficiency.

Recommendations for future works

1. Theoretical formulations on elastic properties of bamboo fiber reinforced concrete.
2. Study on long term properties of BFRC like Creep and Shrinkage.
3. Study on the economical and eco-friendly methods of extracting natural fibers.

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Appendix A: Mix Design

<u>Based on DOE Mix Design procedure</u>

The following tables and figures are design data from DOE mix design manual that were used to proportion C25 concrete grade in this specific research.

Table 2 Approximate compressive strengths (N/mm^2) of concrete mixes made with a free-water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm^2) Age (days) 3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Table 3 Approximate free-water contents (kg/m^3) required to give various levels of workability

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water content is estimated by the expression:

$\frac{2}{3} W_f + \frac{1}{3} W_c$ = 190kg/m³

where W_f = free-water content appropriate to type of fine aggregate
and W_c = free-water content approporiate to type of coarse aggregate.

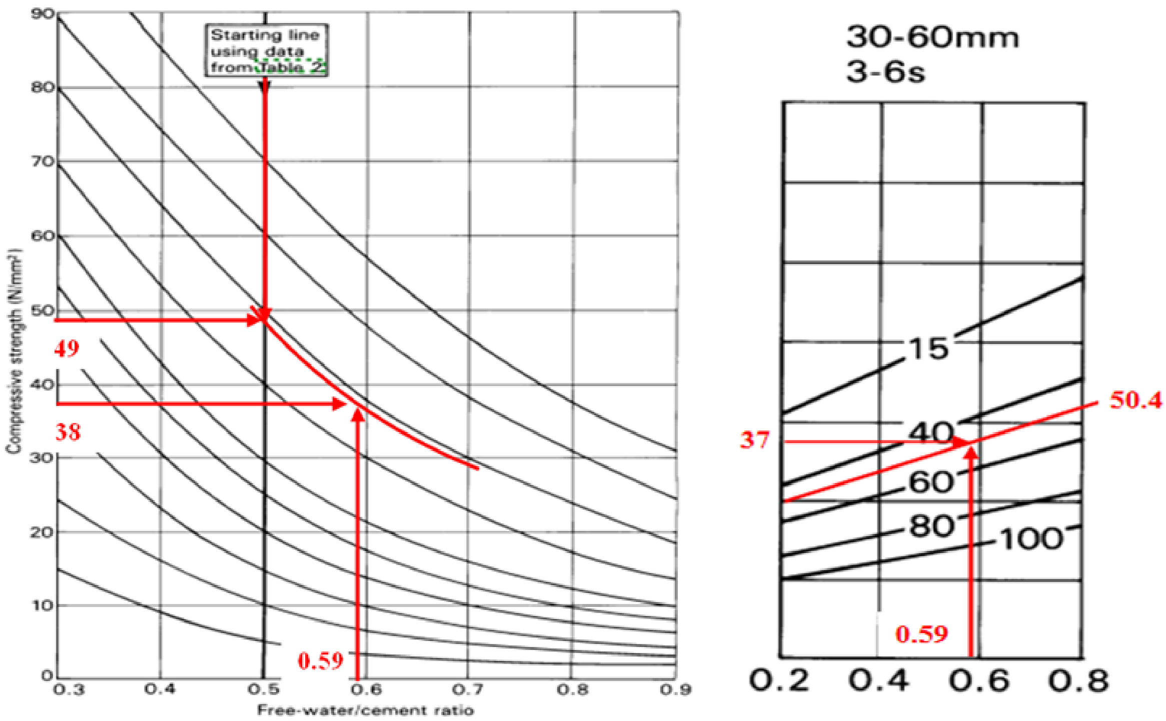


Figure A.1: Compiled mix design data from DOE mix design manual

Completed Mix Design with DOE

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	25 N/mm² at 28 days; Proportion defective 5 percent
	1.2	Standard deviation	Fig 3	/ N/mm² or no data 8 N/mm²
	1.3	Margin	C1	(k=1.64) 1.64 x 8 = 13.12 N/mm²
	1.4	Target mean strength	C2	25 +13.12 = 38.12 N/mm²
	1.5	Cement type	Specified	**OPC**/SRPC/RHPC
	1.6	Aggregate type: coarse		Crushed
		Aggregate type: fine		Uncrushed
	1.7	Free-water/cement ratio	Table 2, fig 4	0.59 (use the lower value)
	1.8	*Maximum free-water/cement ratio*	*Specified*	/ (use the lower value)
2	2.1	Slump or V-B	Specified	Slump 30-60 mm or V-B / s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.59 = 322 kg/m³
	3.2	*Maximum cement content*	*Specified*	/ kg/m³
	3.3	*Minimum cement content*	*Specified*	/ kg/m³ --- use if greater than Item 3.1 and calculate Item 3.4
	3.4	Modified free-water/cement ratio		/
4	4.1	Relative density of aggregate		2.7 ~~known~~/assumed
	4.2	Concrete density	Fig 5	2400 kg/m³
	4.3	Total aggregate content	C4	2400 - 322 - 190 = 1888 kg/m³
5	5.1	Grading of fine aggregate	BS 882	Zone 3
	5.2	Proportion of fine aggregate	Fig 6	37 percent
	5.3	Fine aggregate content	C5	0.37 x 1888 = 698.6 kg/m³
	5.4	Coarse aggregate content	C5	1888 - 698.6 = 1189.4 kg/m³

Quantities	Cement (Kg)	Water (Kg or l)	Fine aggregate (Kg)	Coarse aggregate(Kg)
Per m³ (to nearest 5 Kg)	325	190	700	1190
Per trial mix of ______ m³				

Adjustment with moisture content and absorption capacity of the aggregates

Since the aggregates were neither at SSD condition nor at OD condition in the field, it is necessary to adjust the aggregates weight for the amount of water contained in the aggregate and absorption capacity.

As proportioned with DOE mix design table on appendix A above; weights of constituent materials are listed with Table A.1 as shown below:

Table A.1: Quantities of materials from DOE mix design

Materials	**Weight per 1m^3 of concrete**
Water	190 kg
Cement	325kg
Coarse aggregate	1190 kg
Fine aggregate	700 kg

But in actual condition the aggregate is not in SSD condition. Therefore, predetermined moisture contents and absorption capacity of aggregates are:

Aggregates	**Moisture Content**	**Absorption Capacity**	**Net result for Adjustment**
Fine Aggregate	3.1%	5.26%	2.16%, Absorption
Coarse aggregate	2.04%	1.84%	0.20%, Moisture

Weight of coarse aggregate = 1190* (1+0.20/100) = **1192.4** kg

Weight of fine aggregate = 700* (1-2.16/100) = **685** kg

Adjusted water content = 190 – (1190*0.20/100) + (700*2.16/100) = **202.7** kg

Finally, the quantities to be used for the trial mix per 1m^3 of concrete are shown in Table A.1.

Table A.2: Adjusted quantities of materials to be used in concrete mixing

Materials	**Weight per 1m^3 of concrete**
Water	**202.7 kg**
Cement	**325 kg**
Coarse aggregate	**1192.4 kg**
Fine aggregate	**685 kg**

Appendix B: Test Results

B1: Compressive Strength Tests

Mix code: M_o (0% Bamboo Fiber)

Table B.1: 7th & 28th day Compressive strength test results for 0.0% bamboo fiber

Test age (days)	SN	Dimensions (cm)			Volume (cm^3)	Failure load (kN)	100mm cube Comp. Strength (MPa)	150mm cube Comp. Strength (MPa)
		L	B	D				
7	1	10	10	10	1000	197.8	19.78	18.99
	2	10	10	10	1000	202.9	20.29	19.48
	3	10	10	10	1000	181.0	18.10	17.38
Mean							**19.39**	**18.61**
28	1	10	10	10	1000	253.3	25.33	24.32
	2	10	10	10	1000	265.2	26.52	25.46
	3	10	10	10	1000	266.9	26.69	25.62
Mean							**26.18**	**25.13**

Mix code: M_1 (0.1% Bamboo Fiber)

Table B.2: 7th & 28th day Compressive strength test results for 0.1% bamboo fiber

Test age (days)	SN	Dimensions (cm)			Volume (cm^3)	Failure load (kN)	100mm cube Comp. Strength (MPa)	150mm cube Comp. Strength (MPa)
		L	B	D				
7	1	10	10	10	1000	224.0	22.40	21.50
	2	10	10	10	1000	223.4	22.34	21.45
	3	10	10	10	1000	215.2	21.52	20.66
Mean							**22.08**	**21.20**
28	1	10	10	10	1000	341.9	34.19	32.82
	2	10	10	10	1000	349.2	34.92	33.52
	3	10	10	10	1000	334.5	33.45	32.11
Mean							**34.18**	**32.81**

Mix code: M2 (0.2% Bamboo Fiber)

Table B.3: 7th & 28th day Compressive strength test results for 0.2% bamboo fiber

Test age (days)	SN	Dimensions (cm)			Volume (cm^3)	Failure load (kN)	100mm cube Comp. Strength (MPa)	150mm cube Comp. Strength (MPa)
		L	B	D				
7	1	10	10	10	1000	212.2	21.22	20.37
	2	10	10	10	1000	218.1	21.81	20.94
	3	10	10	10	1000	221.2	22.12	21.23
Mean							**21.72**	**20.85**
28	1	10	10	10	1000	330.2	33.02	31.70
	2	10	10	10	1000	297.4	29.74	28.55
	3	10	10	10	1000	294.0	29.40	28.22
Mean							**30.72**	**29.49**

Mix code: M3 (0.3% Bamboo Fiber)

Table B.4: 7th & 28th day Compressive strength test results for 0.3% bamboo fiber

Test age (days)	SN	Dimensions (cm)			Volume (cm^3)	Failure load (kN)	100mm cube Comp. Strength (MPa)	150mm cube Comp. Strength (MPa)
		L	B	D				
7	1	10	10	10	1000	175.7	17.57	16.87
	2	10	10	10	1000	188.7	18.87	18.11
	3	10	10	10	1000	190.3	19.03	18.27
Mean							**18.49**	**17.75**
28	1	10	10	10	1000	255.8	25.58	24.56
	2	10	10	10	1000	256.5	25.65	24.62
	3	10	10	10	1000	250.2	25.02	24.02
Mean							**25.42**	**24.40**

B2: Splitting Tensile Strength Tests

Mix code: M_0 (0% Bamboo Fiber)

Table B.5: 7th & 28th day Split Tensile strength test results for 0.0% bamboo fiber

Test age (days)	Sample no.	Length (cm)	Diameter (cm)	Volume (cm^3)	Failure load (kN)	Splitting tensile Strength(MPa)
		L	D			$\sigma = 2P/\pi LD$
7	1	30	15	5301.44	140.6	1.989
	2	30	15	5301.44	144.4	2.042
	3	30	15	5301.44	146.5	2.072
Mean						**2.034**
28	1	30	15	5301.44	160.2	2.266
	2	30	15	5301.44	158.6	2.243
	3	30	15	5301.44	149.4	2.113
Mean						**2.207**

Mix code: M_1 (0.1% Bamboo Fiber)

Table B.6: 7th & 28th day Split Tensile strength test results for 0.1% bamboo fiber

Test age (days)	Sample no.	Length (cm)	Diameter (cm)	Volume (cm^3)	Failure load (kN)	Splitting tensile Strength(MPa)
		L	D			$\sigma = 2P/\pi LD$
7	1	30	15	5301.44	149.5	2.116
	2	30	15	5301.44	143.9	2.037
	3	30	15	5301.44	130.6	1.849
Mean						**2.001**
28	1	30	15	5301.44	131.1	1.856
	2	30	15	5301.44	188.7	2.671
	3	30	15	5301.44	169.9	2.405
Mean						**2.311**

Mix code: M_2 (0.2% Bamboo Fiber)

Table B.7: 7th & 28th day Split Tensile strength test results for 0.2% bamboo fiber

Test age (days)	Sample no.	Length (cm)	Diameter (cm)	Volume (cm^3)	Failure load (kN)	Splitting tensile Strength(MPa)
		L	D			$\sigma = 2P/\pi LD$
7	1	30	15	5301.44	141.9	2.008
	2	30	15	5301.44	151.2	2.140
	3	30	15	5301.44	149.5	2.116
Mean						**2.088**
28	1	30	15	5301.44	170.9	2.419
	2	30	15	5301.44	146.6	2.075
	3	30	15	5301.44	152.9	2.164
Mean						**2.219**

Mix code: M_3 (0.3% Bamboo Fiber)

Table B.8: 7th & 28th day Split Tensile strength test results for 0.3% bamboo fiber

Test age (days)	Sample no.	Length (cm)	Diameter (cm)	Volume (cm^3)	Failure load (kN)	Splitting tensile Strength(MPa)
		L	D			$\sigma = 2P/\pi LD$
7	1	30	15	5301.44	137.8	1.950
	2	30	15	5301.44	111.3	1.575
	3	30	15	5301.44	118.3	1.674
Mean						**1.733**
28	1	30	15	5301.44	123.4	1.747
	2	30	15	5301.44	124.1	1.757
	3	30	15	5301.44	137.8	1.950
Mean						**1.818**

B3: Flexural Strength Tests

Mix code: M_0 (0% Bamboo Fiber)

Table B.9: 7th & 28th day Flexural strength test results for 0.0% bamboo fiber

Test age (days)	Sample no.	Dimensions (cm)			Failure load (kN)	Max. Moment (kNm)	Moment of Inertia (cm^4)	Centroidal depth (cm)	Bending Strength (MPa)
		L	B	D	P	M = PL/3	I= $bd^3/12$	c = D/2	σ = Mc/I
7	1	50	10	10	7.221	1.083	833.33	5	6.499
	2	50	10	10	7.267	1.090	833.33	5	6.540
	Mean								**6.159**
28	1	50	10	10	7.406	1.111	833.33	5	6.665
	2	50	10	10	7.33	1.100	833.33	5	6.597
	Mean								**6.631**

Mix code: M_1 (0.1% Bamboo Fiber)

Table B.10: 7th & 28th day Flexural strength test results for 0.1% bamboo fiber

Test age (days)	Sample no.	Dimensions (cm)			Failure load (kN)	Max. Moment (kNm)	Moment of Inertia (cm^4)	Centroidal depth (cm)	Bending Strength (MPa)
		L	B	D	P	M = PL/3	I= $bd^3/12$	c = D/2	σ = Mc/I
7	1	50	10	10	7.445	1.117	833.33	5	6.701
	2	50	10	10	7.379	1.107	833.33	5	6.641
	Mean								**6.671**
28	1	50	10	10	7.487	1.123	833.33	5	6.738
	2	50	10	10	7.774	1.166	833.33	5	6.997
	Mean								**6.8675**

Mix code: M2 (0.2% Bamboo Fiber)

Table B.11: 7th & 28th day Flexural strength test results for 0.2% bamboo fiber

Test age (days)	Sample no.	Dimensions (cm)			Failure load (kN)	Max. Moment (kNm)	Moment of Inertia (cm^4)	Centroidal depth (cm)	Bending Strength (MPa)
		L	B	D	P	M = PL/3	I= $bd^3/12$	c = D/2	σ = Mc/I
7	1	50	10	10	6.413	0.921	833.33	5	5.529
	2	50	10	10	7.256	1.088	833.33	5	6.530
	Mean								**6.029**
28	1	50	10	10	7.181	1.077	833.33	5	6.463
	2	50	10	10	8.268	1.240	833.33	5	7.441
	Mean								**6.952**

Mix code: M3 (0.3% Bamboo Fiber)

Table B.12: 7th & 28th day Flexural strength test results for 0.3% bamboo fiber

Test age (days)	Sample no.	Dimensions (cm)			Failure load (kN)	Max. Moment (kNm)	Moment of Inertia (cm^4)	Centroidal depth (cm)	Bending Strength (MPa)
		L	B	D	P	M = PL/3	I= $bd^3/12$	c = D/2	σ = Mc/I
7	1	50	10	10	6.99	1.049	833.33	5	6.291
	2	50	10	10	7.94	1.191	833.33	5	7.146
	Mean								**6.719**
28	1	50	10	10	8.121	1.218	833.33	5	7.309
	2	50	10	10	7.612	1.142	833.33	5	6.851
	Mean								**7.080**

Appendix C: Tests for Constituent Materials

Aggregate needs to be standardized because concrete strength and quality depends on physical properties, mechanical properties and chemical composition of the parent aggregate making materials. All physical tests conducted for both fine & coarse aggregates were discussed by the following session.

C1: Tests for Coarse Aggregates

Basaltic crushed stones of nominal maximum size 19mm were prepared for the use in this specific research. Physical properties like gradation, specific gravity, water absorption, moisture content and unit weight of the aggregates were tested.

i. Sieve Analysis

Sieve Analysis is a procedure for the determination of the particle size distribution of aggregates using a series of square or round openings starting with the largest. According to the Ethiopian Standard coarse aggregates are those between 75 and 4.75 mm in size

Test Results:

Table C.1: Particle size distribution for coarse aggregate

Sieve size (mm)	Weight of Sieve (gm)	Wt. Of sieve and retained (gm)	Weight Retained (gm)	Percentage Retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)
37.5			0	0	0	**100**
19	1389	1439	100	5	5	**95**
12.5	1166	1766	600	30	35	**65**
9.5	1173	1873	700	35	70	**30**
4.75	1175	1615	440	22	92	**8**
Pan	735	895	160	8	-	**-**
				Total	**202**	

Calculation:

F.M = $\frac{\sum cummulative\ coarser\ (\%)}{100} = \frac{202}{100} = 2.02\%$

Where: F.M = the Fineness Modulus of the aggregate

A requirement from the Ethiopian Standard for grading coarse aggregate regarding ranges of percentage passing through each sieves are presented in Table C.2 as shown below.

Table C.2: Ethiopian Standard for grading of coarse aggregate (ES C.D3. 201)

Nominal size of Aggregate, mm	Percentage passing through test sieves having square openings						
	75mm	63mm	37.5mm	19mm	13.2mm	9.5mm	4.75mm
38 – 5	100	-	95 – 100	30 – 70	-	10 – 35	0 – 5
19 – 5	-	-	100	95 – 100	-	25 – 55	0 – 10
13 – 5	-	-	-	100	90 – 100	40 – 85	0 – 10

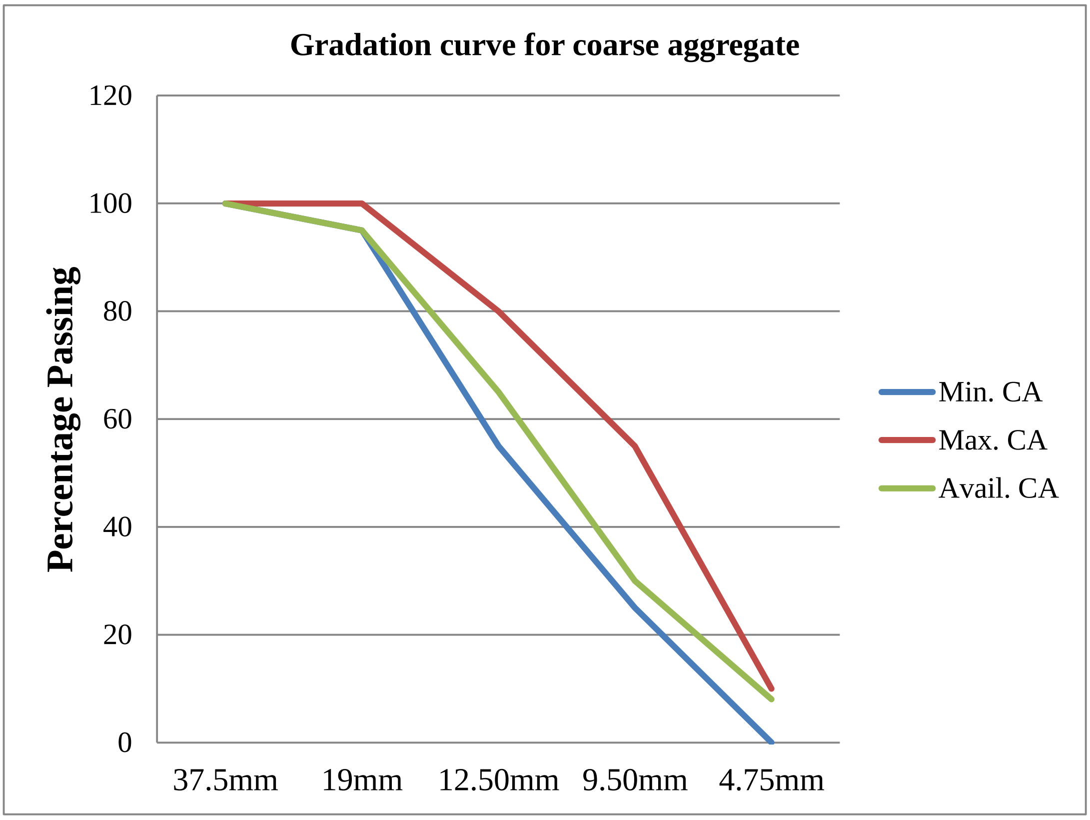


Figure C.1: Gradation curve for coarse aggregate

Comment

All the coarse aggregate samples were blended to keep gradation requirement within the range and hence it is basic to prepare good quality concrete.

ii. Specific gravity and water absorption

The specific gravity of a substance is the ratio between the weight of the substance and that of the same volume of water. Absorption is the process by which water is drawn into and tends to fill the permeable pores in a porous solid body.

An approximate aggregate sample of 5kg was aquired, by using quartering from the mass sample. All aggregate materials passing N0. 4 (4.75 mm) sieve were rejected

Test Results: Where:

A = 4936 g A = weight of oven-dry sample in air, [g]

B = 5027 g B = weight of saturated-surface-dry sample in air, [g] and

C = 3230 g C = weight of saturated sample in water, [g]

Calculation:

Bulk Specific Gravity

$$Bulk\ sp\ gr = \frac{A}{B-C}$$

$$Bulk\ sp\ gr = \frac{4936}{5027-3230} = \mathbf{2.76}$$

Bulk Specific Gravity (Saturated – Surface –Dry basis):

$$Bulk\ sp\ gr\ (SSD\ basis) = \frac{B}{B-C}$$

$$Bulk\ sp\ gr\ (SSD\ basis) = \frac{5027}{5027-3230} = \mathbf{2.80}$$

Apparent Specific Gravity:

$$Apparent\ sp\ gr = \frac{A}{A-C}$$

$$Apparent\ sp\ gr = \frac{4936}{4936-3230} = \mathbf{2.89}$$

Absorption Capacity:

$$Absorption\ Capacity\ (\%) = \frac{B-A}{A} * 100$$

$$Absorption\ Capacity\ (\%) = \frac{5027-4936}{4936} x100 = \mathbf{1.84}\%$$

iii. Moisture Content of coarse aggregate:

The objective of this test is to determine the moisture content of coarse aggregate

Test Results:

A = 2000 g

B = 1960 g

Where:

A = weight of original sample [g]

B = weight of oven dry sample [g]

w = Moisture content (%)

Calculation:

$$w\ (\%) = \frac{A-B}{B} * 100$$

$$w\ (\%) = \frac{2000 - 1960}{1960} x100 = 2.04$$

Comment:

Aggregates were washed to remove dirt particles, and hence well dried in the sun. Moisture content and absorption capacity of coarse aggregate sample are used in concrete mix-design to specify the amount of mixing water and water cement ratio.

iv. Unit weight of aggregates

The unit weight measures the volume that the graded aggregate will occupy in concrete and includes both the solid aggregate particles and the voids between them. This method is applicable to aggregates of 40 mm maximum size.

Test Results:

Weight of the Measuring apparatus = 4841 gm.

Weight of sample + Measuring apparatus = 28054 gm.

Calculation:

Dimension of the measuring apparatus:

- Inside diameter = 253mm
- Inside height of the measure = 275mm

Volume of the measuring apparatus:

$$V = \frac{\pi D^2 h}{4} = \frac{3.14\ x\ 0.253^2\ x\ 0.275}{4} = 0.01382\ m^3$$

$$Unit\ weight\ of\ C - agg. = \frac{28054 - 4841}{0.01382} = \mathbf{1679.67\ kg/m^3}$$

C2: Tests for Fine Aggregates

i. Silt content

The objective of this test is to determine the silt (finer than No. 200 sieve) content in sand.

Test results:

A = 10ml

B = 290ml

Where:

A = amount of silt deposited above the sand

B = amount of clean sand

Calculation:

Silt content (%) = $\frac{A}{B} * 100$

$$Silt\ Content\ (\%) = \frac{10}{290}\ X\ 100 = 3.45 < 6 \ldots\ldots OK!$$

According to the Ethiopian Standard, if the silt content of the sand is more than 6% it is recommended either to wash or to reject the sand. The sand in this specific research can be used without washing since silt content is less than 6%.

ii. Sieve analysis

The objective of the test is to determine the particle size distribution of fine aggregates. Table C.3 and Table C.4 below summarize the particle size distribution as per the Ethiopian Standard for the grading of coarse aggregate.

Test results:

Table C.3: Particle size distribution for coarse aggregate

Sieve size (mm)	Weight of Sieve (gm)	Wt. Of sieve and retained (gm)	Weight Retained (gm)	Percentage Retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)
9.5	585	585	0	0	0	**100**
4.75	426	434	8	1.6	1.6	**98.4**
2.36	388	407	19	3.8	5.4	**94.6**
1.18	372	432	60	12	17.4	**82.4**
0.6	325	486	161	32.2	49.6	**50.4**
0.3	301	493	192	38.4	88	**12.0**
0.15	272	321	49	9.8	97.8	**2.2**
Pan	243	254	11	2.2	_	**_**
				Total	**259.8**	

Fineness modulus F.M = $\frac{\sum cummulative\ coarser\ (\%)}{100}$

$$= \frac{259.8}{100} = \quad 2.598 \cong 2.60$$

Sieve size	9.50mm	4.75mm	2.36mm	1.18mm	600mm	300mm	150mm
Percentage passing	100	95 – 100	80 – 100	50 – 85	25 – 60	10 – 30	2 – 10

Table C.4: The Ethiopian Standard for grading of fine aggregate (ES C.D3. 201)

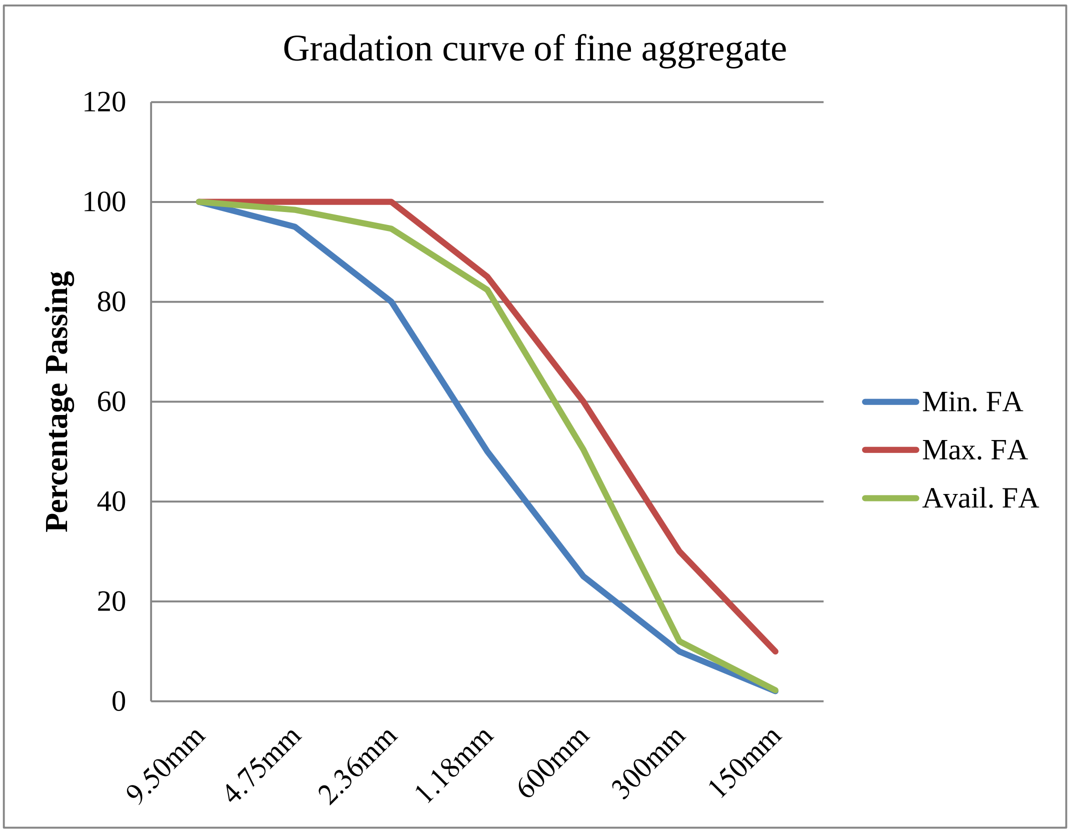


Figure C.2: Gradation curve for fine aggregate

Comment:

The sand sample purchased was tested to check if the material has a particle size distribution within the range of the Ethiopian Standard for the grading of fine aggregate. Thus it satisfies the gradation requirement.

iii. Specific gravity and absorption capacity

The objective of this test is to determine bulk and apparent specific gravity, and absorption capacity of the fine aggregates.

Sample tests were prepared and the procedures for the setup were followed in accordance with the guide of Construction Materials Laboratory Manual by Abebe Dinku. Test results were presented as shown below.

Test results:

Weight of the sample = 500g

Test results for the computation of specific gravity & absorption of fine aggregate

W = 320g

V = 975.39 ml

Va =769.80 ml

A = 475 g

Where,

W = weight of pycnometer, gm.

V = volume of flask/container

Va = volume of water added to pycnometer [cm^3]

A = weight of oven dry sample in air [g]

Calculation:

C = 0.9976Va + 500 +W

= 0.9976*(769.80) + 500 + 320

= 1587.95g

B = 0.9976V + W

= 0.9976*(975.39) + 320

= 1293.05g

Where, C = weight of pycnometer filled with sample plus water, [gm]

B = weight of flask filled with water, [gm]

Bulk specific gravity:

$$Bulk\ sp\ gr = \frac{A}{B + 500 - C}$$

$$Bulk\ sp\ gr = \frac{475}{1293.05 + 500 - 1587.95} = \mathbf{2.32}$$

Bulk Specific gravity (Saturated-Surface-Dry Basis):

$$Bulk\ sp\ gr\ (SSD\ Basis) = \frac{500}{B + 500 - C}$$

$$Bulk\ sp\ gr\ (SSD\ Basis) = \frac{500}{1293.05 + 500 - 1587.95} = \mathbf{2.44}$$

Apparent specific gravity:

$$Apparent\ sp\ gr\ (SSD\ Basis) = \frac{A}{B + A - C}$$

$$Apparent\ sp\ gr = \frac{475}{1293.05 + 475 - 1587.95} = \mathbf{2.64}$$

NB: In the computation of quantities for concrete mixes it is the specific gravity of Saturated Surface Dry (SSD) aggregates that is always used.

Absorption:

$$Absorption\ Capacity\ (\%) = \frac{500 - A}{A} x100$$

$$Absorption\ Capacity\ (\%) = \frac{500 - 475}{475} x100 = \mathbf{5.26}$$

iv. Moisture content

The objective of this test is to determine the moisture content of fine aggregate.

Test results:

A = 500 g

B = 485 g

Where:

A = weight of original sample [g]

B = weight of oven dry sample [g]

Calculation:

$$w\ (\%) = \frac{A - B}{B} * 100$$

Where:

w = Moisture content (%)

$$\boldsymbol{w}\ (\%) = \mathbf{3.1}$$

Appendix D: Sample photo gallery taken during the Research

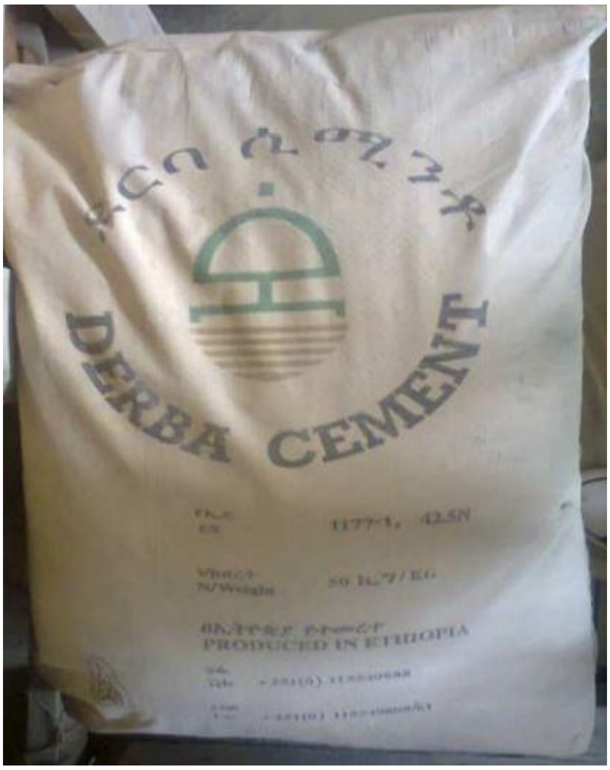
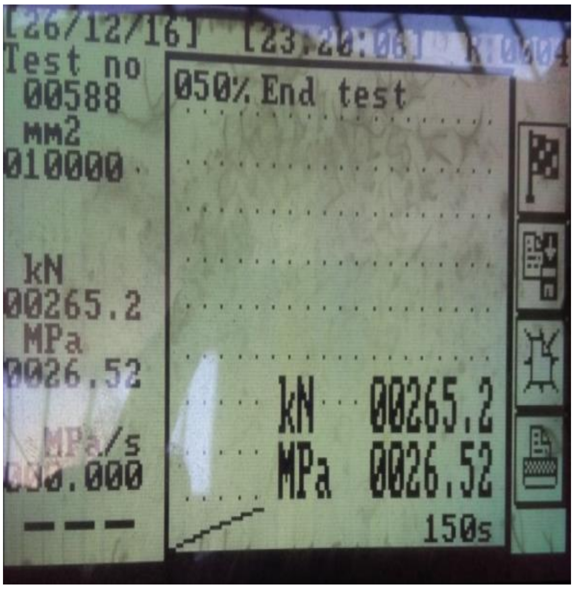


Photo: Cement used in the mix

Photo: Mechanical mixer



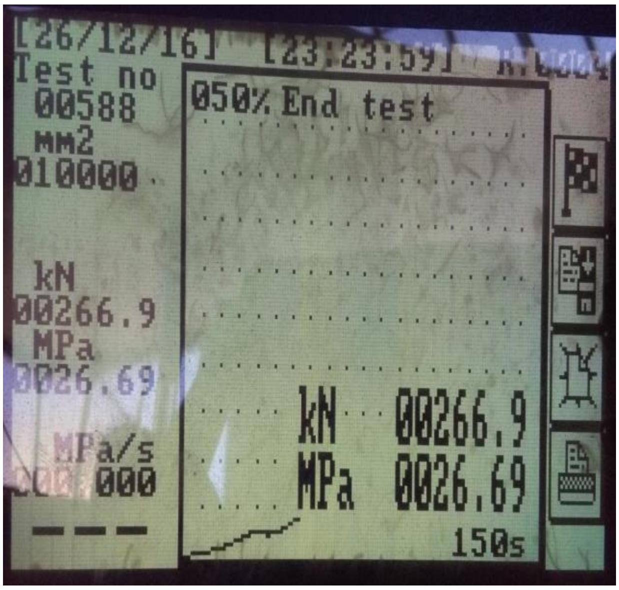
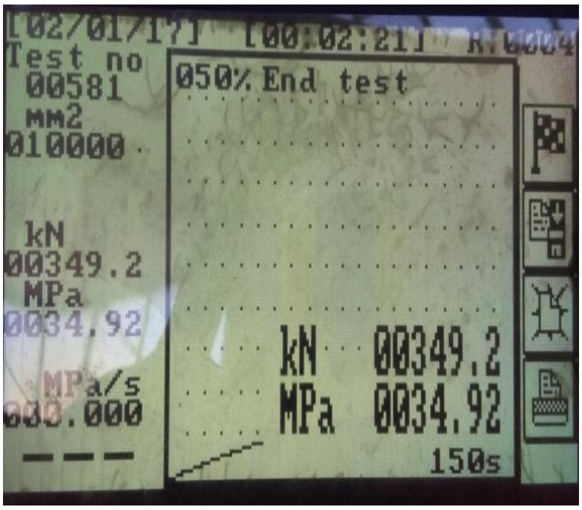


Photo: Compressive Strength test results for representative samples of control mix M_0



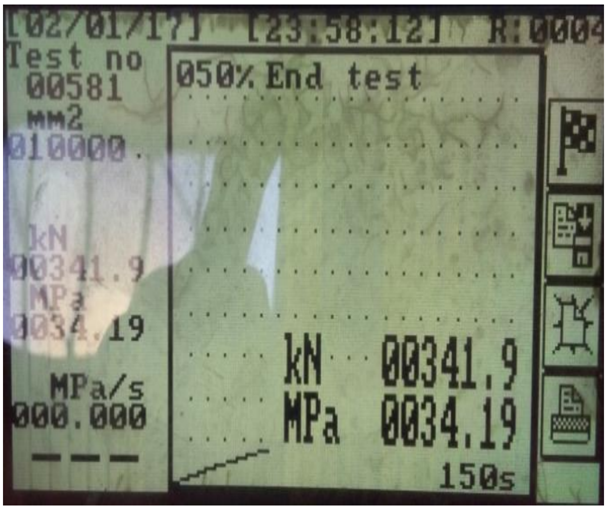
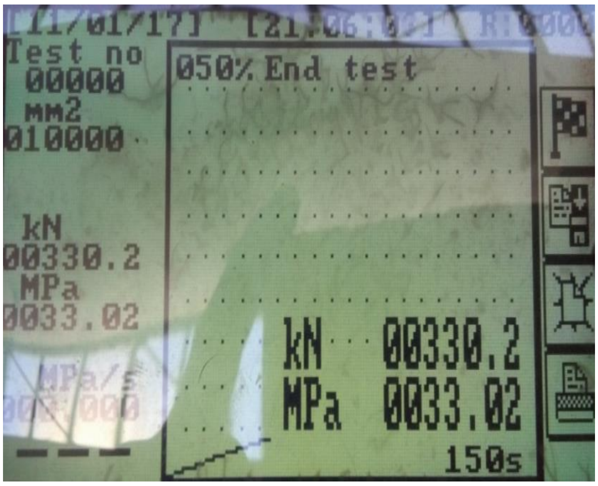


Photo: Compressive Strength test results for representative samples of mix M_1



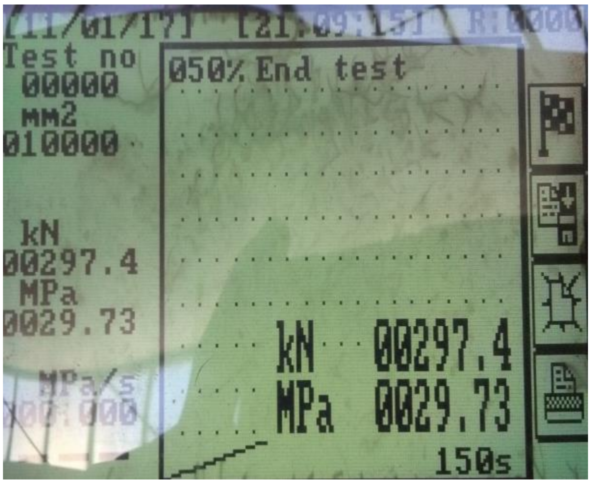
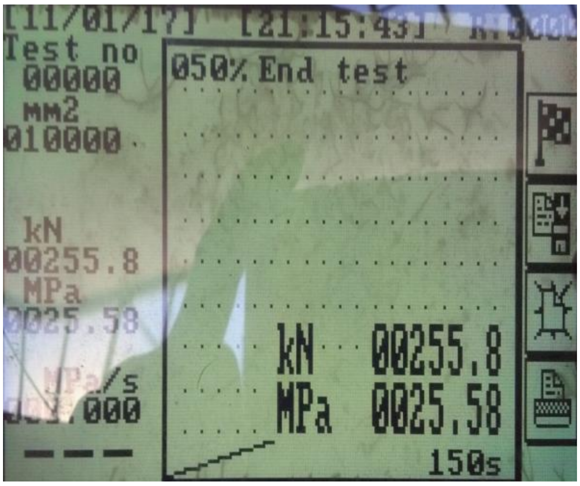


Photo: Compressive Strength test results for representative samples of mix M_2



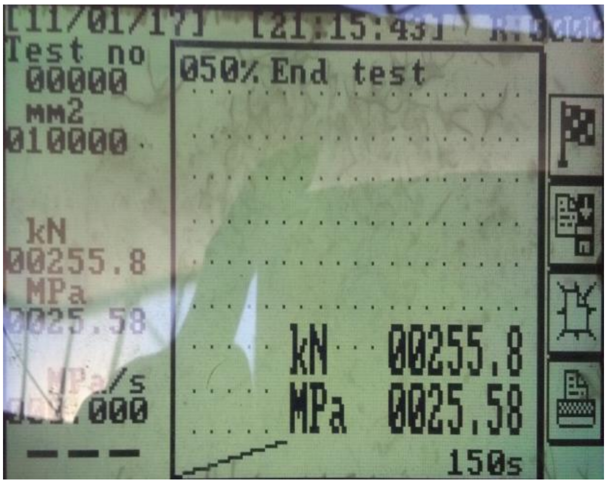


Photo: Compressive Strength test results for representative samples of mix M_2

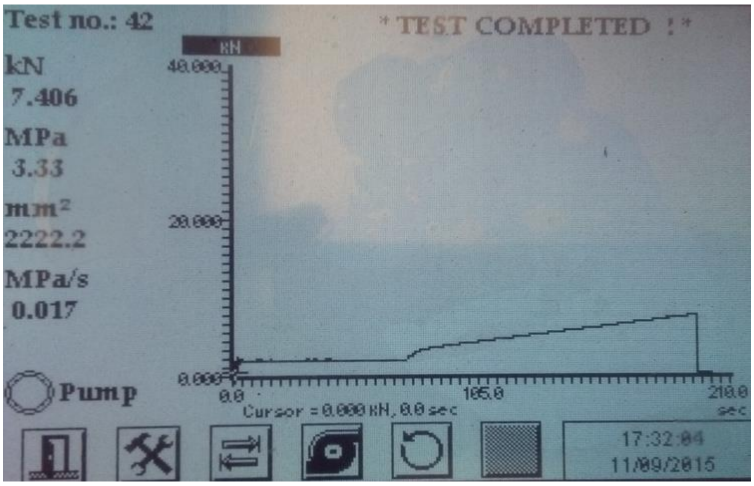
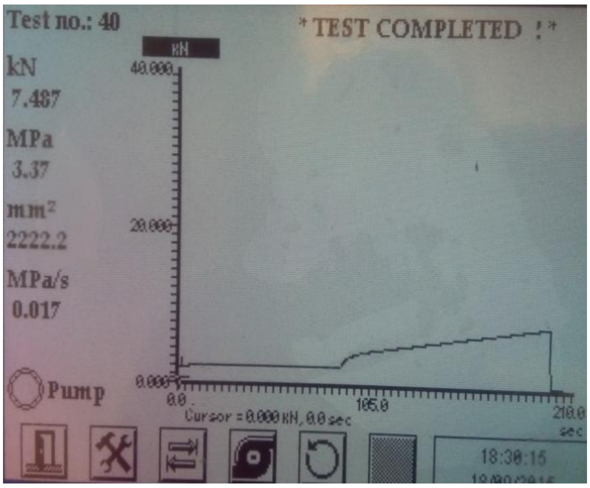


Photo: Flexural Strength test results for representative samples of mix M_0



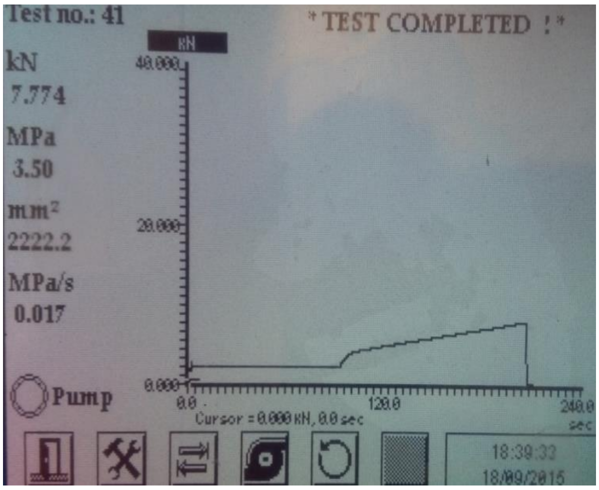
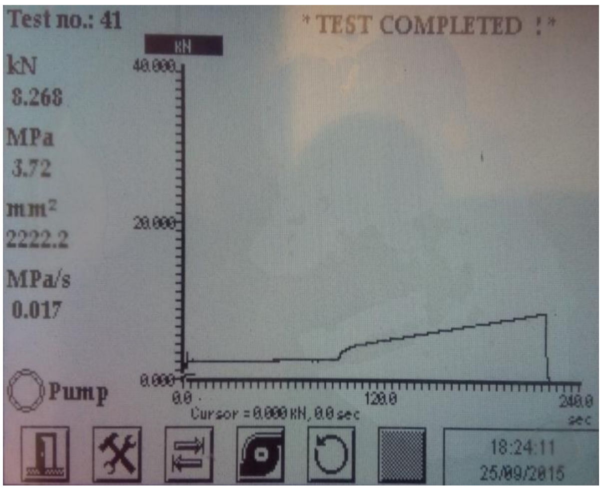


Photo: Flexural Strength test results for representative samples of mix M_1



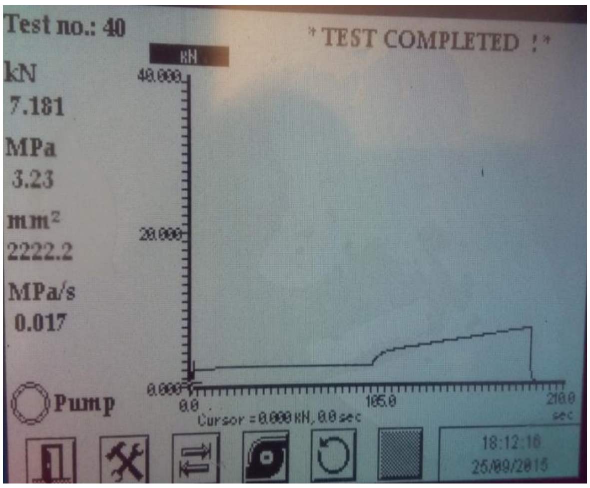


Photo: Flexural Strength test results for representative samples of mix M_2

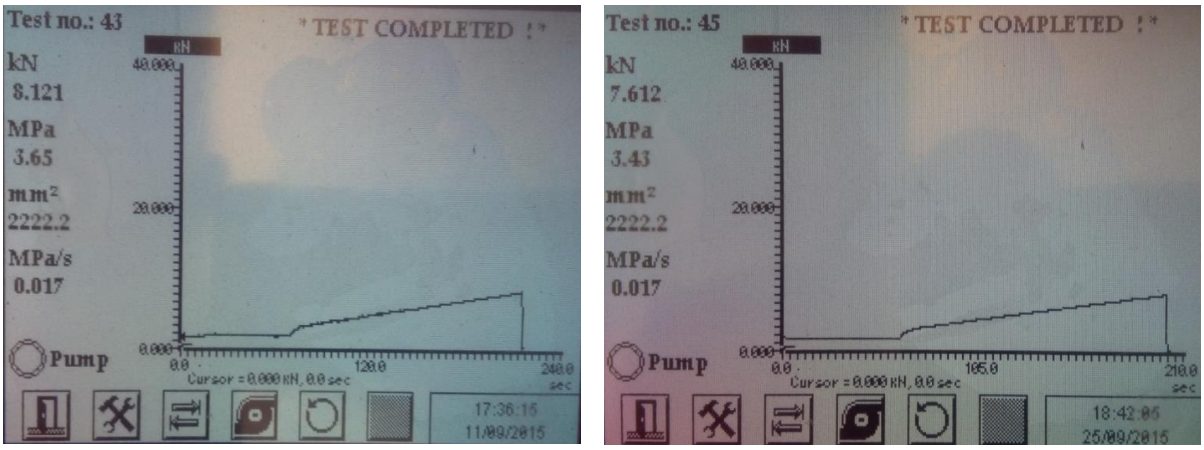


Photo: Flexural Strength test results for representative samples of mix M_3

Photo: Split Tensile Strength test results for representative samples of mix M_1

Photo: Split Tensile Strength test results for representative samples of mix M_2

Photo: Split tensile strength testing machine and cylindrical specimens after loading

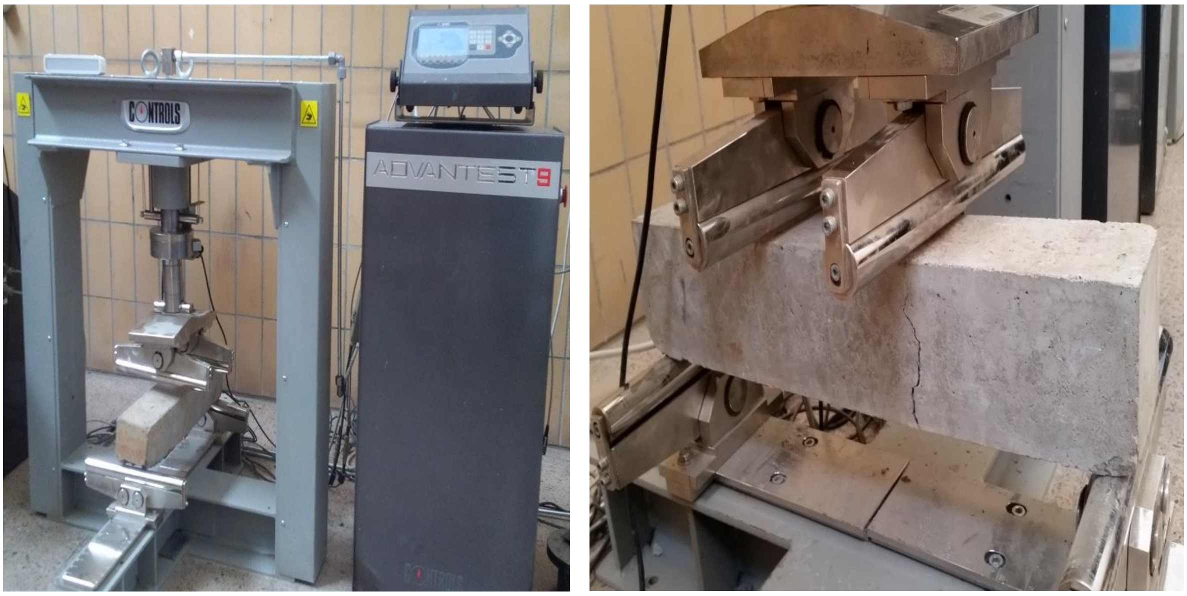


Photo: Flexural strength testing machine and beam under third-point loading

Photo: Compressive strength testing machine and cube samples under loading