STRENGTH AND FRACTURE OF EARTH-BASED AND NATURAL FIBER-REINFORCED COMPOSITES

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DECLARATION

I hereby declare that the matter embodied in this thesis entitled "Strength and Fracture of Earth-based and Natural Fibre-reinforced Composites" is the result of investigation carried out by me under the supervision of Professor Winston Oluwole Soboyejo at African University of Science and Technology, Abuja and that it has not been submitted elsewhere for the award of any degree or diploma.

In keeping with the general practice in reporting scientific observation, due acknowledgement has been made whenever the work described is based on the findings of other investigators.

_____

Mustapha Kabiru

ACKNOWLEDGEMENT

In the name of Allah (SWT), the Most Gracious and Most Merciful. All praise is due to Allah (SWT), the Lord of the world, who honoured mankind and favoured them markedly above a great part of His creation. May His peace and blessing be upon His noble prophet Muhammed, his entire household, companion and those who follow him till the end of time (Amin).

My immense gratitude goes to my parents for all their contributions during the entire period of my studies. Also, to all members of my family and friends for their love, care, encouragement and support. May Allah reward them abundantly (Amin).

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ABSTRACT

This study examined the mechanical properties of earth-based materials that are relevant to the future development of affordable housing. Earthcrete structures were produced by mixing various proportions of laterites, clay and cement, while natural fibre-reinforced composites were produced by mixing earth-based matrices with natural fibre (Straw). Mechanical testing showed that optimum performance of the various samples was obtained at a fibre content of 20% by volume, with compressive strength values of about 2.91 MPa, flexural strength values of about 34.4 MPa and fracture toughness in the range of 1.40 – 1.50 MPa$\sqrt{m}$. The results indicate that the mechanical performance of the composites being studied is in line with those in prior studies on natural fiber-reinforced cementious matrix composites.

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

In our society today, the choice of materials for building is greatly influenced by the cost, properties (mechanical and chemical) and availability. Industrialized societies have developed various materials which are applied in all works of construction (including buildings). Unfortunately, developing countries such as Nigeria where alternative materials exist have failed to explore such opportunities even when there is the possibility of producing such, locally. There is therefore, a need to explore new ways of producing robust building materials from locally available materials.

Such needs have stimulated recent efforts to develop affordable building materials that are strengthened and toughened by locally available natural fibers (Savastano et al., 2003) and matrix materials that are available in developing countries. However, in most cases, the matrix materials utilize cement, which is a relatively expensive synthetic material that emits ~ 14% of the CO_2 emissions that are thought to contribute to global warming.

In contrast, earth-based materials are readily available materials that could be used as matrix material in building composites. They can also be stabilized by the use of binders, such as dung or cement, to produce materials that are strong and tough enough for applications in buildings. They can also be reinforced with natural fibers (such as sisal and straw) or industrial wastes (saw dust), while the matrices can be optimized by the use

of industrial wastes, such as blast furnace slag and crushed charcoal from the burning of wood.

1.2 PROBLEM STATEMENT

There has been great progress in both the production and application of reinforced materials (except little for earth-based materials). In most cases where high strength and toughness of earth-based materials are required, the materials are stabilized with cement or dung (John, 2001). Some local people have also used straw and other natural fibers to strengthen earth-based materials that are used in local construction of earthen homes.

However, the scientific and engineering bases for such application are very limited. There is, therefore, a need to develop the scientific understanding that can provide the necessary basis for the design of novel earth-based materials that can be used in rural and urban construction.

1.3 SCOPE OF WORK

This study examines the effect of processing, composition and natural fiber reinforcement on the strength and fracture toughness of natural fiber-reinforced earth-based composites. The study includes:

1. The processing of local (earth-based) materials with different compositions;
2. The material characterization of local materials and processed materials with:
    I. X-ray diffraction (XRD) analysis;
    II. Scanning electron microscopy (SEM);

III. Energy Dispersion X-ray Spectroscopy (EDS).

3. The measurements of the strength of the samples produced. In this study, two (2) forms of strength will be considered. These are:

   I. Compressive strength.

   II. Bend/Flexure strength.

4. The determination of the fracture toughness of the different samples produced, and

5. A study of toughening mechanism using indentation crack growth technique.

CHAPTER TWO

2.0 LITERATURE SURVEY

2.1 EARTH-BASED MATERIALS

Earth-based materials are naturally occurring materials found on the earth. They are vital resources (raw materials) that provide the basic component of life, agriculture and industry. These materials include minerals, rocks, soil and water. This study focus on soils which could be used as alternative building materials. The earth-based materials to be studied include laterite, clay and straw.

2.1.1 LATERITE

Laterites are soil type rich in iron and aluminum. They are formed in hot and wet tropical areas. Nearly all laterites are rusty-red because of the iron oxide contained in them. They develop by intensive long-lasting tropical weathering of the underlying parent rocks. Tropical weathering (laterization) is a prolonged process of mechanical and chemical weathering which produce a wide variety in the thickness, grade, chemistry and mineralogy of the resulting soils. Laterites cover about one-third of the earth's continental land area, with the majority of that in the land areas between the tropics of Cancer and Capricorn.

Francis Buchanan Hamilton first described and named laterite formation in southern India in 1807. He named it laterite from the Latin word "Later", which means a brick. Thick rock can be easily cut into brick-shaped blocks for building (Thurston, 1913). Historically, laterite was cut into brick-like shapes and used in monument buildings.

When moist, laterites can be easily cut into regular-sized blocks. Upon exposure to air, it gradually hardens as the moisture between the particles evaporates and the larger iron salts lock into a rigid lattice structure and become resistant to atmospheric conditions (Tardy, 1997). The act of quarrying laterite material into masonry is suspected to have been introduced from the Indian subcontinent.

After 1000 CE, construction at Angkor Wat and other south-east Asian sites changed to rectangular temple enclosures made of laterite bricks and stones. Since the mid-1970s, trial sections of bituminous-surfaced low volume roads have used laterite in place of stones as base course (Grace, 1991). Thick laterite layers are porous and slightly permeable, so layers can function as aquifers in rural areas. Locally available laterites are used in an acid solution followed by precipitation to remove phosphorous and heavy metal at sewage treatment facilities (Wood et al, 1996).

2.1.2 CLAY

In simple terms, clay is seen as a naturally occurring earth material composed primarily of fine-grained particles (minerals). It differs from other soils by difference in size and mineral content. Clay is typically formed over long period of time by gradual weathering (chemical or physical) of rocks. In addition to the weathering process, some clays are formed by hydrothermal activities. Clay deposits may be formed in places as residual deposits in soils but thick deposits usually are found as a result of secondary sedimentary deposition process after they must have been eroded and transported from their original location of formation. With respect to location, clay soils can be classified as either primary or secondary. Primary clay (Kaolin) is located at the site of formation while

secondary clay deposits have been moved by erosion from their primary location (Guggenheim and Martin, 1995).

Elemental compositions of clay minerals are same as that of hydro aluminum phyllosilicate with variable amount of iron, magnesium, alkali metals, alkali earth and other cations. Structurally, they are composed of two dimensional sheets of corner sharing SiO_4 and AlO_4 tetrahedra. The resulting tetrahedral sheets give a chemical composition of $(Al, Si)_3O_4$. The tetrahedral sheets are always bonded to octahedral sheets formed from small cations, such as aluminum or magnesium, coordinated by six oxygen atoms (Moore and Reynolds, 1997).

Clay soils finds applications in varieties of ways. They exhibit plasticity when mixed with water in certain proportions. When dry, clay becomes firm and when fired in Kiln, permanent physical and chemical reactions occurs which cause it to be converted into ceramic materials. Clay also serves as binders when used in matrices. As a result of these properties, clay is used for making pottery items, both for utilization and decoration. Bricks, cooking pots, art objects, dishware, etc can all be shaped from clay before being fired. Recent studies have investigated clay's absorption capacities in various applications such as the removal of heavy metals from waste water and air purification. Also, clay finds application in medicine and agriculture (Hillier, 2003).

2.1.3 STRAW

Straw is the dry stalks of cereal plants. It is an agricultural by-product obtained after the grain and chaff have been removed. Straw makes up about half of the yield of cereal

crops such as barley, oats, rice, and wheat. It has many uses, including fuel, livestock bedding and fodder, thatching and basket-making. Straw can also be used to bind clay and concrete in the production of building materials. Mechanically, straw filament breaks when subjected to a force of about 0.25 kg/mm2 by which it extended 4% of its original length (Schiesser et al., 1989).

2.2 COMPOSITE CONCEPTS

The desire for specified material properties has lead to the unusual combination of materials. This is especially true for materials needed for many of our modern day technologies. This desire has lead to the production of certain special materials known as composites. A composite material is made by combining two or more materials to give unique combination of properties. This definition is found to be more general and can include metal alloys, plastic co-polymers, minerals and wood. One of the most unique composites is fiber-reinforced. They differ from the earlier mentioned materials in that their constituent materials are different at molecular level and are mechanically separable. The constituent materials together provide the desired properties but remain in their original forms. The final properties of the composite materials are better than the constituent materials properties (Sanjay, 2002). This study will focus on fibre-reinforced composites.

The main concept of a composite is that it is made up of matrix materials. Most composites are formed by reinforcing fibers in a certain matrix resin. The reinforcements can be fibers, particulates or whiskers and the matrix material can be metals, plastics or

ceramics. The figure below shows a schematic diagram illustrating the formation of a composite.

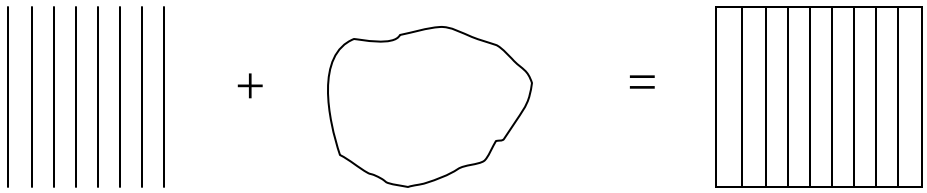


Fig. 2.00: Formation of a composite material

In a composite, the fibers can be continuous, long or short. All these or only one form can be used in a composite. Most importantly is to note that the fiber carries the load and its strength is greatest along the axis of the fiber. The figure below shows the fiber forms in a composite.

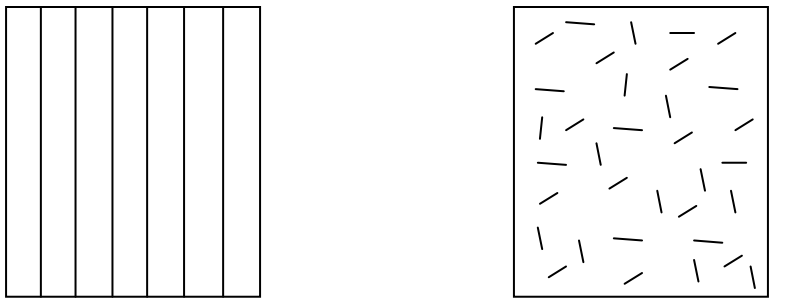


Fig. 2.01: Fiber forms in a composite

Long continuous fibers in the direction of the load results in a composite with properties far better than the plain matrix. The same is obtainable with the shorter fibers except that it provides properties less better than that offered by the continuous fibre composites. The fiber form is selected depending on the application and manufacturing method.

2.2.1 FUNCTIONS OF FIBRES AND MATRIX IN COMPOSITES

As stated earlier, composite materials are formed by reinforcing certain matrix with a desired fiber. There is therefore the need to understand the roles of fibers and matrix materials in a composite. Some of the main features of the fibers in a composite material are:

- ✓ To carry the load.
- ✓ To provide stiffness, strength, thermal stability and other structural properties in the composite.
- ✓ To provide electrical conductivity or insulation, depending on the type of fiber used.

The matrix on the other hand fulfills several functions in a composite structure which are essential in attaining the desired performance of the structure. The functions of the matrix material in a composite include the following:

- ✓ The matrix material binds the fibers together and transforms the load to them.
- ✓ It isolates the fibers so that individual fibers can act independently. This function is very important because it helps stops or slows the propagation of cracks in a structure.
- ✓ The matrix provides a good surface finish quality and help in giving the structure its shapes.

- ✓ It provides protection to the reinforcing fibers against chemical and mechanical damage.
- ✓ It influences the performance characteristics such as ductility and impact strength of the composite. These characteristics will largely depend on the matrix material used.
- ✓ The failure mode is strongly affected by the type of matrix material as well as its compatibility with the fiber.

(Sanjay, 2002)

2.2.2 RULE OF MIXTURES

During composite formation, it is very important to ensure that particles have approximately the same dimension in all direction. It is also necessary to make particles small and evenly distributed throughout the matrix so as to achieve an effective reinforcement. Another important parameter necessary for consideration during composite formation is the volume fraction of the two phases. This is so because mechanical properties are influenced by changes in particulate content. For a two phase composite, two mathematical expressions have been developed for the effect of volume fraction of the constituent phases on the elastic modulus of the composite (Callister, 2007). These expressions make up what is referred to as the rule of mixture. These rules (equations) predict that the elastic modulus should fall between an upper and lower bound represented by equations [2.00] and [2.01] respectively.

$$E_c(u) = E_m V + E_p V_p \qquad [2.00]$$

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \qquad [2.01]$$

In the above expressions, E and V denote the elastic modulus and volume fraction respectively. The subscripts c, m and p denote the composite, matrix and particulate respectively. Below is a schematic illustrating the upper and lower bound moduli given by the rule of mixture (Callister, 2007).

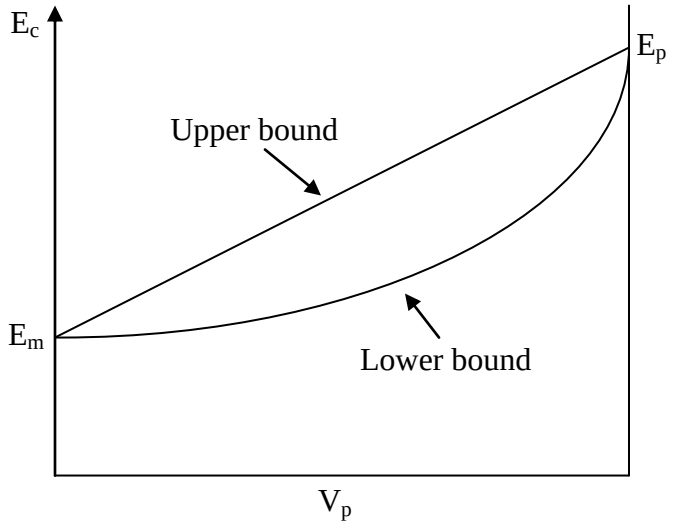


Fig. 2.02: Schematic illustration of lower and upper bound moduli

2.3 STRENGTH OF MATERIALS

The strength of a material is one of the most important property of the material that is studied in material science. It refers to the ability of a material to withstand an applied stress without failure. It is measured in N/m^2 of MPa (1 MPa = 10^6 N/m^2). An applied stress may be compressive, tensile or shear. The strength of a material is also dependent on its microstructure. There is alteration in the microstructure of a material when it is

subjected to an engineering process. Therefore, there is the need for strengthening mechanisms that alters the strength of materials. These mechanisms include work hardening, solid solution strengthening, grain boundary strengthening and precipitation hardening (Timoshenko, 1976).

However, the strength of materials often refers to various methods of calculating stresses in structural members such as beams, columns and shafts. This can be used to predict the response of structures during loading. In the determination of material strength, the type of loading influences the type of stress experienced by the material. These types of loading are possible:

I. Transverse loading: In this case, the applied forces are perpendicular to the longitudinal axis of a member. It causes the member to bend and deflect from its original position, with internal tensile and compressive strains accompanying change in curvature. Below is a schematic diagram describing transverse loading. The arrows indicate the direction in which the loads are acting.

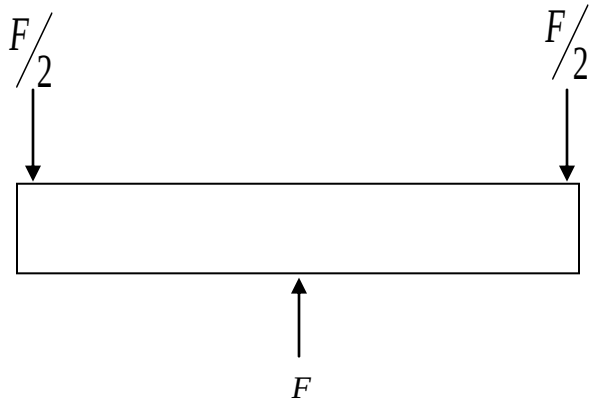


Fig. 2.03: Schematic describing transverse loading

II. Axial loading: The applied forces in this case are collinear with the longitudinal axes of the members. It causes member to either stretch or shortens. Fig. 2.4a and 2.4b below presents a schematic illustration of the action of axial loading.

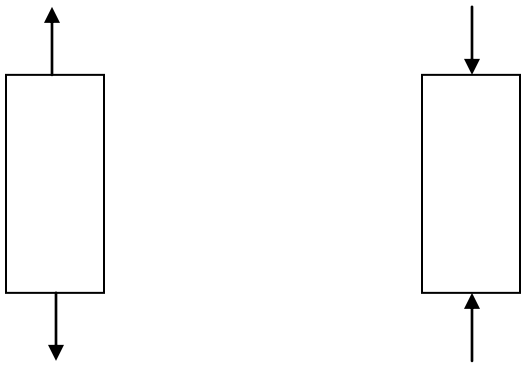


Fig. 2.04: Schematic illustration of axial loading

III. Torsional loading: In this case, twisting action occurs which is caused by the application of externally equal and oppositely directed couples acting in parallel plains or by a single external couple applied to a member that has one end fixed against rotation. Fig. 2.5 shows the direction of torsional loading. The arrows indicate the direction of the applied load.

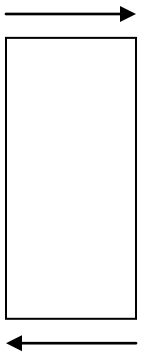


Fig. 2.05: Schematic illustration of the action of torsional loading.

When the strength of a material is to be determined, the type of stress applied is essential parameter which corresponds to the strength of the material. The following are the types of stress applicable in the determination of a material strength (Bear and Johnson, 2006).

I. Compressive stress: This is a stress state which resulted from an applied load that acts to reduce the length of the material in the axis of the applied load. A simple case is the uniaxial compression induced by the action of opposite, pushing forces (see fig. 2.4b). the compressive strength is obtained from the uniaxial stress which is expressed by:

$$\sigma = F/A \qquad [2.02]$$

Where F is the applied force (N) acting on an area, A (m^2). The area can be the undeformed or the deformed area depending on whether engineering or true stress is used.

II. Tensile stress: This is the stress state caused by the application of a load that tends to elongate the material. The strength of a material when considered in terms of tensile stress can be in form of either uniaxial or bend/flexure strength.

The uniaxial tensile strength can be calculated using equation [2.02]. The diagram below shows the action of transverse loading to aid in the calculation of bend/flexure strength (Hibbeler, 2004).

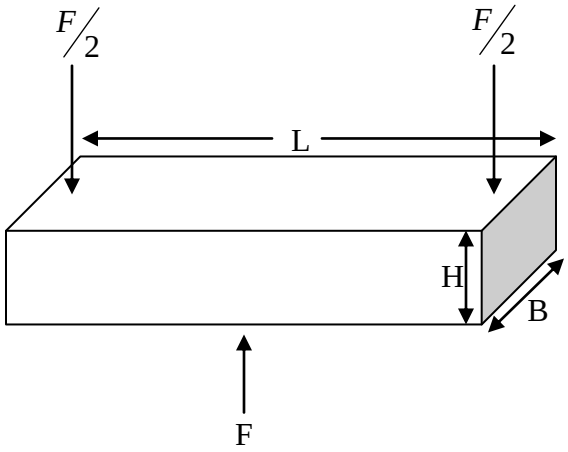


Fig. 2.06: Transverse loading of a beam showing the parameters needed to calculate its flexure strength.

The maximum bending moment (M) of the applied force (F) about the mid-point of the bar is given by:

$$M = F/2 \times L/2 \qquad [2.03]$$

Where L is the length of the bar. The second moment of area (I_{zz}) of the cross section acting along the z-axis is given by:

$$I_{zz} = \frac{BH^3}{12} \qquad [2.04]$$

Where B and H are the breath and height of the bar respectively. By combining equations [2.03] and [2.04], the bend/flexure strength is given by:

$$\text{Bend/Flexure Strength } (\sigma_{max}) = \frac{My_{max}}{I_{zz}} \qquad [2.05]$$

Where y_{max} is the distance from centre of the specimen to outer fibers given by:

$$y_{max} = H/2 \qquad [2.06]$$

III. Shear stress: Is the stress state caused by a pair of opposing forces acting along parallel lines of action through the material. It results from the sliding faces of the material relative to one another. The strength of the material in this case can be obtained by using equation [2.02].

2.4 FUNDAMENTALS OF FRACTURE MECHANICS

In material science, fracture is a very important concept which plays a big role in the life expectancy of a material during application. It is regarded as a process in which an increase in loading suddenly causes accelerated growth of pre-existing crack. Studies have shown that three distinct phases are revealed when a material is loaded. These are:

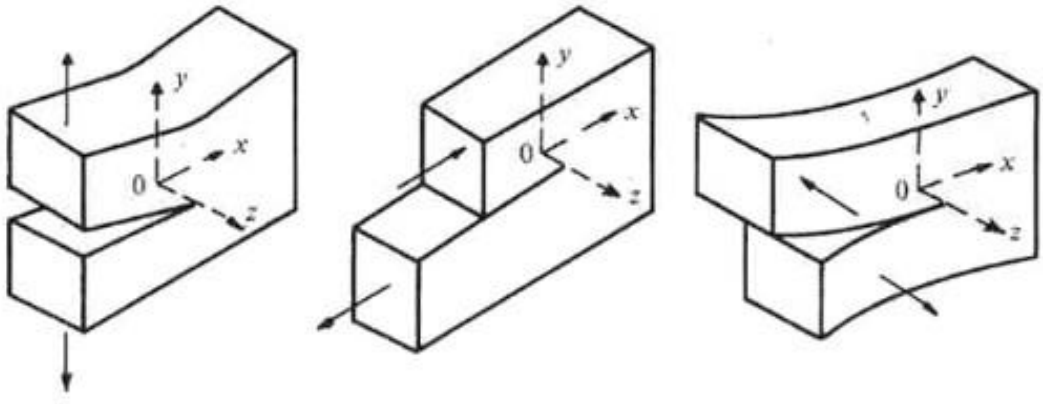
- ✓ Loading without crack growth.
- ✓ Stable crack growth.
- ✓ Unstable crack growth.

In principle, stable crack growth may be controlled with the aid of a loading device so that a prescribed slow crack growth may be obtained. For an unstable crack growth, this is not possible because the process occurs spontaneously (Dieter, 1986).

2.4.1 PRE-EXISTING CRACKS

All real materials contain defects which makes pre-existing cracks very common and virtually impossible to avoid in large structures. In some solids, tiny surface cracks appear spontaneously as a result of chemical agent. In some other cases, cracks are opened as a result of thermal stresses created after heat treatment (hardening) or welding. They are also formed during the manufacturing of materials or as a result of mechanical processes during manufacturing or joining of structural parts.

Hence, there is the need to understand the initiation and growth of cracks. Also, it is important to understand the influence of these defects on the strength of the material. First to be considered when studying cracks is the fracture mode. The mode of separation of the crack surfaces is known as the mode of fracture. It is also very important to know which mode of fracture is resulting from a particular loading. The three possible modes of fracture are shown in fig. 2.7 below.



(a) (b) (c)

Fig. 2.07: Modes of fracture

MODE I (Fig. 2.07a): This is known as the tensile opening mode. The crack faces separate in a direction normal to the plane of the crack. The displacements are symmetric with respect to the x-z and x-y planes.

MODE II (Fig. 2.07b): This is known as the in-plane sliding mode. The crack faces in this case are mutually sheared in a direction normal to the crack front. The displacements are symmetric with respect to the x-y plane and anti-symmetric with respect to the x-z plane.

MODE III (Fig. 2.07c): This mode is referred to as the tearing or anti-plane shear mode. In this case, the crack faces are sheared parallel to the crack front. The displacements are anti-symmetric with respect to the x-y and x-z planes.

It is also very important to note that combination of modes (mixed-mode loading) is possible (Dieter, 1986).

2.4.2 FRACTURE TOUGHNESS

During the application of fracture mechanical principles, an expression which relates the critical stress (σ_c) during crack propagation to the crack length (a) was developed. This expression is written as:

$$K_c = Y\sigma_c\sqrt{\pi a} \qquad [2.07]$$

In the above expression, K_c is known as the fracture toughness or the stress intensity factor. It is a property that is a measure of a material's resistance to fracture when a crack is present. It also provides a numerical value, which quantifies the magnitude of the effect

of the stress singularity at the crack tip. Fracture toughness has an unusual unit of $MPa\sqrt{m}$ or $psi\sqrt{in}$ (Callister, 2007).

Furthermore, Y is a function of the crack length, "a", and width, "W". It is a dimensionless parameter that depends on the size and geometry of the specimen. It also depends on the manner in which the load is applied. This function is also known as geometry function. Geometry functions for various fracture mechanics can be found in fracture mechanics handbooks. For this study, where a bend specimen is considered, the ASTM standard E399-81, Annual Book of ASTM standards, Part 10, 1981 is used (Soboyejo, 2002). The geometry function for single edge notched bend geometry (SENB) is given by:

$$Y = f\left(\frac{a}{w}\right) = \frac{3\left(a/w\right)^{1/2}}{2\left(1+2a/w\right)\left(1-a/w\right)^{3/2}} \times \left[1.99 - \left(a/w\right)\left(1-a/w\right)\left(2.15 - 3.93\,a/w + 2.7\,a^2/w^2\right)\right]$$

[2.08]

2.4.3 DETERMINATION OF STRESS INTENSITY FACTOR

With respect to this study, an experimental approach will be considered in the determination of stress intensity factor. In order to achieve this (i.e. find critical value of K), an increasing load F is applied to an SENB specimen, which has an initial crack of known length, a_o, already introduced. The load at which the specimen fracture is recorded.

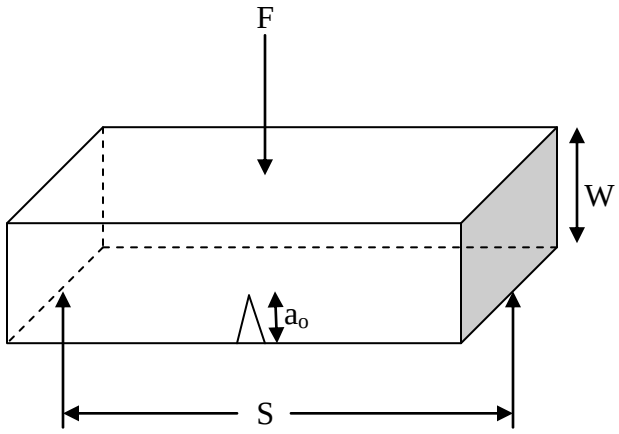


Fig. 2.08: Single edge notched beam (SENB)

Figure 2.08 shows a beam specimen loaded so that the side in which a crack has been placed is in tension. Equations [2.05] and [2.07] allows the fracture toughness to be calculated from the crack length, a, and load, F at which fracture of the specimen occurs (Antony, 2007).

2.5 TOUGHENING MECHANISMS

In order to improve the low intrinsic toughness of materials, extrinsic toughening techniques that provide crack-tip shielding mechanisms are often developed. Such mechanisms, which include crack bridging via ductile or brittle reinforcements, primarily act behind the crack tip and locally shield the crack from the applied driving force. Figure 2.09 shows a schematic representation of the model of crack bridging.

During toughening of materials, it is apparent to note that the source of the toughness in the material is associated principally with the crack tip shielding that result from the bridging in the wake of the crack. Quantitatively, the contribution to the toughness as a

result of the crack bridging can be obtained by calculating the reduction in the near-tip intensity K_b, caused by the appropriate crack surface traction stress distribution.

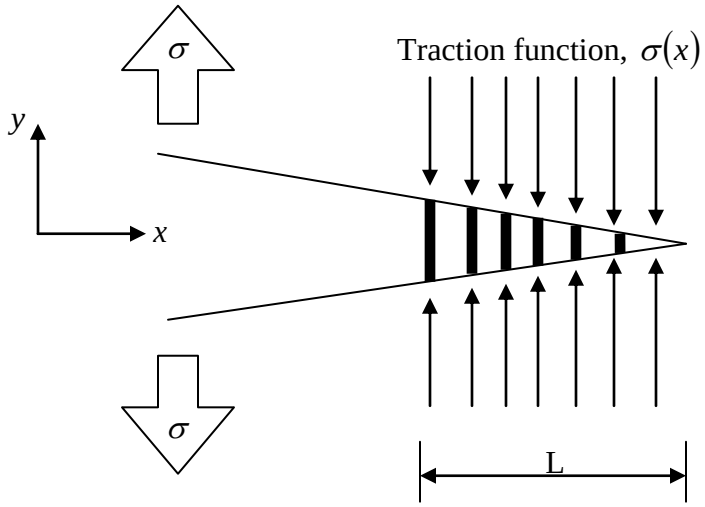


Fig. 2.09: Schematic representation of the model used to determine the shielding contribution provided by bridging ligaments in the wake of a crack

The problem depends on the given traction distribution, crack length and specimen geometry. Generalized solutions employ weight function to calculate the stress intensity reduction resulting from the shielding for any form of traction function. The bridging contribution is formulated as (Fett and Munz, 1994):

$$K_b = \int_0^L \sigma(x) h(a, x) dx \qquad [2.09]$$

Where $\sigma(x)$ is the traction function at distance x behind the crack tip, $h(a.x)$ is the weight function and the integration limits are determined by the bridging zone length, *L*. If the shielding contribution is superposed with the intrinsic toughness of the composite, the measured toughness, $K_{c,app}$ for a given loading condition is given by:

$$K_{c,app} = K_o + K_b \qquad [2.10]$$

Where K_o is taken to be the crack initiation toughness of the composite. Computation of equation [2.10] requires the knowledge of the traction function, $\sigma(x)$ which in turn depends on the stress displacement behavior, $\sigma(u)$ of the bridging ligaments and the crack opening profile, $U(x)$. The functions are generally obtained by the direct measurement of the crack-opening profile of the system under loading (Bannister et al, 1992). A simplified approach to this problem is to assume that $\sigma(x)$ is a constant function and uniformly active over the bridging zone (Zok and Hom, 1990); the magnitude of the traction function is then equal to some characteristic flow parameter, σ_c which is effectively the constrained flow stress of the reinforcement. It can also be taken as the uniaxial yield or flow strength of the material used for reinforcement. The discreteness of the reinforcement is accounted for by multiplying by the volume fraction, V_f of the reinforcement. With this assumption, the $\sigma(x)$ becomes $V_f \sigma_c$ and equations [2.09] and [2.10] can be rewritten as:

$$K_{c,app} = K_o + V_f \sigma_c \int_0^L h(a,x)dx \qquad [2.11]$$

2.6 INDENTATION INDUCED CRACKING

This is a toughening mechanism that makes use of the theory of indentation hardness to measure the fracture toughness of a material. Material hardness is defined as its resistance to penetration or permanent deformation. Various methods have been employed in the

measurement of material hardness. These include the Brinell, Rockwell and Meyer tests. However, micro hardness can be measured using the Knoop and the Vickers indentation techniques. Micro hardness simply refers to the hardness of a small area. In this study, the Vickers indentation hardness measurement technique will be considered because it has been used extensively in research for predicting fracture toughness of brittle materials (N. Perez, 2004).

The prediction of fracture toughness for many brittle materials using empirical formulations can be obtained in varieties of books. However, the most common expression is the general form expressed as (Ponton and Rawlings, 1989):

$$K_c = \alpha\left(\frac{E}{H_v}\right)^{1/2}\frac{P}{a^{3/2}} \qquad [2.12]$$

Where α is the indentation geometric factor ($\alpha = 0.016$ for a Vickers pyramidal indenter, $\alpha = 0.040$ for a cube-corner indenter), E is the modulus of elasticity, P is the indenter load, H_v is the Vickers hardness and a, is the average crack length.

In the determination of K_c, both E and H are needed. They can be determined from the analysis of the indentation data. This implies that from one test, all these quantities, E, H and K_c can be obtained.

The determination of the modulus of elasticity is based on the Hertz contact equation (Gdoutos, 2005). The equation is given by:

$$E = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}} \qquad [2.13]$$

Where A is the contact area and S is the stiffness of the material giving by:

$$S = \frac{dP}{dh} \qquad [2.14]$$

The hardness can be determined using the Vickers indentation technique. The indentation is made with a diamond pyramidal-shaped indenter. Figure 2.10 shows a schematic diagram of the indenter impression

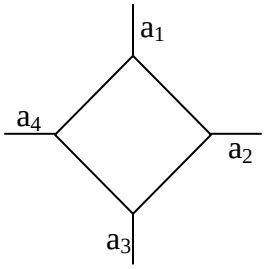


Fig. 2.10: Schematic indentation-induced cracking system

For brittle materials, indentation-induced cracking overcomes difficulties in specimen penetration in a conventional manner. As a result, an empirical equation may be used (N. Perez, 2004). The Vickers hardness (H_v) can be calculated as follows:

$$H_v = \frac{2PSin\left(\theta/2\right)}{D^2} \qquad [2.15]$$

Where P is the applied load, D is the mean diagonal and θ is the face angle. The Vickers hardness measurement is found to be advantageous in varieties of ways (N. Perez, 2004). These include its simplicity, ability to be applied to micro structural constituents and it does not require fatigue pre-cracking, which is difficult to accomplish in brittle materials.

Also, it is cost effective since the specimens are small and the tests are seen as non-destructive in a macro scale.

2.7 PRIOR WORK ON THE REINFORCEMENT OF EARTH-BASED MATERIALS

When materials are produced, there is always great focus on the need to attain optimum mechanical properties such as strength and toughness. In recent times, building materials have undergone various forms of optimization with most attention on the introduction of different types of reinforcements. A report in Forest Products Newsletter in 1986 indicated that most developed countries have adopted wood fiber reinforced cement (WFRC) products obtained by Hatschek (or wet) process for building purpose (Coutts RSP, 1986). In an attempt to provide an alternative for low cost building materials, Agopyan and John reported the use of natural fiber reinforced cement based materials (NFRC). This was prepared with low alkali cements to check the issue of fiber degradation (Agopyan and John, 1992).

In the year 2000, Savastano et al. investigated the possibility of using Brazilian waste fibers as reinforcement for cement-based composites. In this work, they made use of different types of Brazilian fibrous residues. These are the Sisal (Agave Sisalana) field by-product, Banana (Musa cavendishii) pseudo-stem fibers and waste Eucalyptus grandis pulp. The specimens used are natural fiber reinforced cement composites with fiber mass fractions ranging from 4 to 12% prepared by a slurry vacuum de-watering technique. Also, net matrix was produced as a control using the same procedure. The flexural properties and fracture toughness of the materials were studied 28 days after manufacture. The result of the study shows that; at a content of 8%, all the fibre studied

provided a considerable increase in flexural strength (at least 65%) relative to that of the unreinforced matrix. Also, fracture toughness was significantly enhanced by fiber inclusion; at 12% fiber loading, fracture toughness values exceeded 1.0-1.5 kJm^{-2}, a 25-fold increase in energy absorption over the measured values of the brittle matrix material. The results also show that, of the waste fibers studied, E. grandis is the preferred reinforcement for low cost fiber-cement (Savastano et al, 2000).

In a related study, Banthia and Sheng used the resistance curve approaches to study the effects of polypropylene fiber as reinforcements in a cement based matrix. They employed the use of about 3% by volume of fiber content, their results showed a significant improvement in composite toughness. At such level of reinforcement, a fracture toughness of about 1.9MPa $\sqrt{m}$ was obtained (Banthia and Sheng, 1996).

The performance of low-cost vegetable fiber-cement composites under weathering was studied by Savastano et al (2001). They made use of mechanical pulps from sisal (Agava sisalana) and banana (Musa cavendishii) crop wastes and also residual kraft Eucalyptus grandis from a wood pulp mill as reinforcements. Composites were prepared via a slurry vacuum de-watering process followed by pressing and air-curing. They made use of fiber content varying from 8 to 12% by mass. In this study, mechanical testing revealed an improvement in mechanical properties compared to plain matrix. Flexural strengths in excess of 18 MPa were recorded and fracture toughness values in the range of 0.51 to 1.25 kJ/m^2 were obtained after 28 days (Savastano, 2001).

In the same year, a report by Savastano et al (2001) presented a study in which ground iron blast furnace slag was investigated as a matrix for cellulose cement materials. In the

study, high quality soft wood fibers and residual sisal from agricultural waste were chemically pulped and used as reinforcements. Composites based on several different formulations were investigated and the optimum strength and fracture toughness properties were obtained at fiber contents between 8 and 12%. The optimum strength has values in the range of 14.7 – 24.5 MPa while fracture toughness was found to be between 1.13 – 2.36 kJ/m^2 (Savastano et al., 2001).

In 2003, Salvastano et al investigated the potential of alternative fiber cements as building materials for developing areas. They evaluated the performance of thin fiber-cement elements produced from alternative raw materials. They made use of sisal, banana fibers and Eucalyptus grandis pulp as reinforcement. Also, granulated blast furnace slag was used as the major component of an alternative hydraulic binder and ordinary Portland cement was used as a control. The result of the work showed that at fiber content of 8 – 12% by mass, modulus of rupture (MOR) of up to 23 MPa and fracture toughness values in the range of 0.6 - 1.7 kJ/m2 were obtained a 28 days (Savastana et al., 2003).

Most recently, Savastano et al (2009) studied the fracture and fatigue of natural fiber-reinforced cementious composites. The composites used in the study include blast furnance slag cement reinforced with pulped fibers of sisal, banana and bleached eucalyptus, and ordinary Portland cement composites reinforced with bleached eucalyptus pulp. Results from the study showed that the reinforced composites exhibits initiation fracture toughness levels between about 1.6 and 1.9 MPa$\sqrt{m}$. This is considered significantly greater than that of the plain cement paste (0.2 – 0.3 MPa$\sqrt{m}$)

(Nelson et al, 2002). The natural fiber-reinforced composites are tougher than the plain matrix because of crack-bridging that resulted from the crack growth process. The trend in the prediction of resistance curve (stress intensity factor Vs crack growth) behavior obtained from the various forms of bridging models were in agreement with the corresponding experimental measurements (Savastano et al., 2009).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 RAW MATERIALS

The earth-based materials used in this study were collected directly from their deposition sites in Ogun state, South-West Nigeria. These materials are laterite, clay and straw. The laterite and clay were obtained from their deposition sites and then processed before they were used in the sample preparation. The laterite was obtained from Obada as wet soil. It was sun dried for three days and then sieved without crushing. The clay used was obtained from Olurunda Ayetoro. It was also acquired as wet soil with particles bonded together forming different sizes of moulds. These large moulds were broken into smaller pieces and sun dried for two weeks. They were then crushed into fine particles and sieved. The sieve used in the soil preparation had a pore size of 6 mm by 6 mm.

The straw used was obtained from an abandoned farmland at Ibara Orile and was also sundried to remove leaves in it. In addition, a bag of Portland cement (produced by West African Portland Cement Company Plc, Lagos, Nigeria) was obtained from a cement store. Figure 3.00 shows the pictures of the earth materials used.

(a) Laterite (b) Clay (c) Straw

Fig. 3.00: Photographs of earth materials used (1x)

In this study, the raw materials acquired were used to mould bricks of different material compositions (matrices and composites). The samples prepared are to be characterized and mechanically tested to obtain their compression strength, flexural strength and fracture toughness. Sample preparation involved molding bricks into shapes as shown in Figure 3.01.

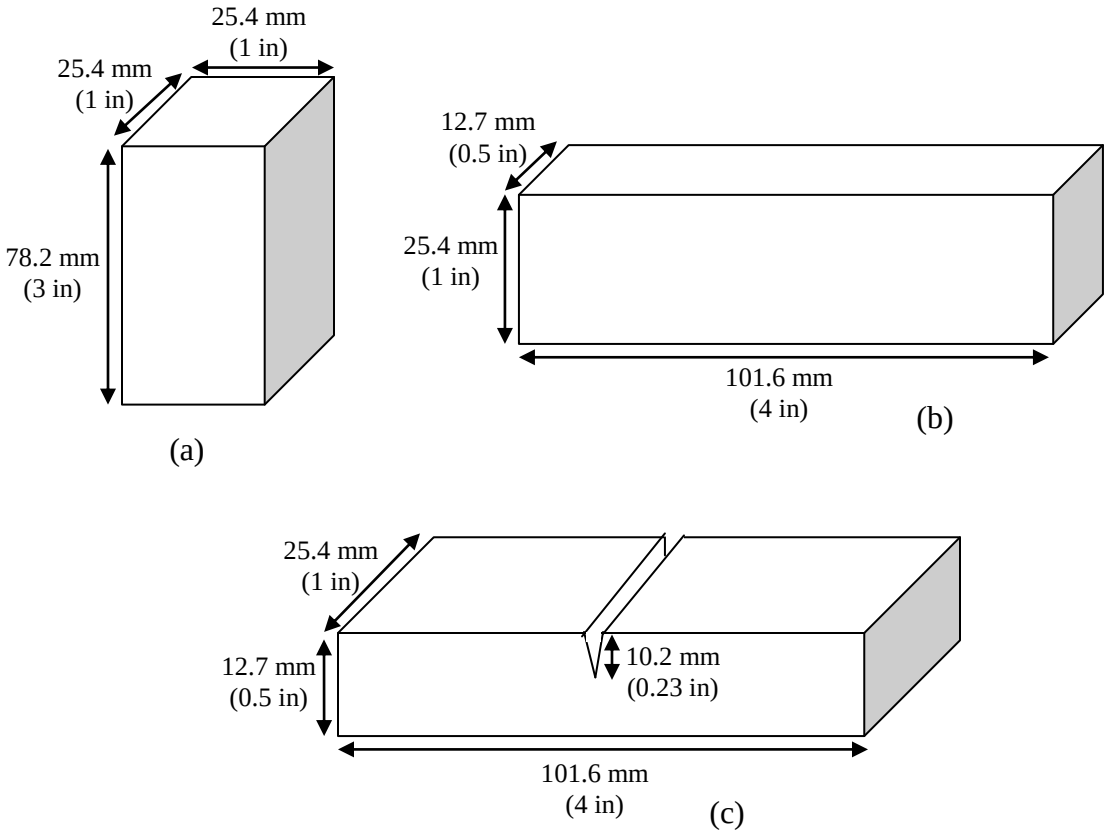


Fig. 3.01: Shapes of samples prepared

The samples were obtained with the aid of a locally made mould. The mould was constructed to correspond to the shape and size of the samples to be made. A hydraulic press was used to press the material firmly so that the resulting sample could take the shape of the molder.

3.2 MATRIX PREPARATION

In this study, different matrix compositions were produced to serve as the control samples to the reinforced ones. The matrices were prepared by the direct mixing of desired material(s) with appropriate amount of water. The mixtures werethen molded to the required sample shapes. The material composition in the matrix preparation was based on percentage composition by volume of laterite, clay and cement. The matrix compositions used are listed below:

1. 100% laterite

2. 100% clay (fired for 6 hours at 800^{o}C)

3. Laterite and cement were combined in different proportions by volume. Table 3.00 shows the percentage compositions by volume of the materials used.

Samples	Volume of laterite used (%)	Volume of cement used (%)
I	80	20
II	90	10
III	95	5

Table 3.00: Percentage composition by volume of laterite and cement in the matrix samples.

4. Laterite, clay and cement were also combined in different proportions by volume. Table 3.01 shows the percentage compositions by volume of the materials used.

Samples	Volume of laterite (%)	Volume of clay (%)	Volume of cement (%)
I	70	10	20
II	60	20	20
III	50	30	20

Table 3.01: Percentage composition by volume of laterite, clay and cement used in the matrix samples.

3.3 COMPOSITE PREPARATION

Natural fiber (straw) reinforced matrix composites with fiber volume fractions ranging from 5% to 20% were produced. During the process, the matrix materials were added to the appropriate amount of fiber. The fibers had been cut to smaller sizes with the aid of a knife so as to obtain shorter fiber composites. In order to study the effect of the reinforcement, the percentage composition by volume of the fibre was varied. Two cases of matrix compositions were considered for the reinforcement. These are:

1. Matrix containing 80% laterite and 20% cement.

2. Matrix containing 70% laterite, 10% clay and 20% cement.

In both cases, samples were prepared with composite (matrix and fiber) compositions as shown in Table 3.02.

Samples	Volume of matrix (%)	Volume of fiber (%)
I	95	5

II	90	10
III	80	20

Table 3.02: Percentage composition by volume of matrix and fiber in the composite samples.

All samples (with the exception of the fired clay) where left to dry for duration of 28 days before they were mechanically tested and characterized.

3.4 MECHANICAL TESTING

The mechanical properties tested in this study were compressive strength, flexural strength and fracture toughness. An electromechanical testing machine (Tiratest model 2810 universal testing machine) was used to test the samples. This was used to measure the compressive and flexural strengths, as well as the fracture toughness of the different materials. A photograph of the system is shown in Figure 3.02.

Fig. 3.02: Picture of Tiratest (Instron) model 2810 Universal testing machine.

In the determination of compressive strength, the compression specimens were deformed (see Fig. 2.04b) at a loading of 200.00 N/min until fracture occurred. A curve of compressive load (kN) versus compressive displacement (mm) was then used to determine the peak load. The compressive stress at the maximum compressive load was taken to correspond to the compressive strength of the material, which was estimated from equation [2.02].

A three point bend loading configuration was used to determine the flexural strength and fracture toughness of the samples. A loading span of 80 mm (Figure 2.06) was used for the entire three point bend test. The mechanical properties (flexural strength and fracture toughness) were measured 42 days after the fabrication of the specimens. The specimens were deformed monotonically to failure at a loading rate of 3 N/s. For each matrix and composite formulation, 3-5 specimens were tested.

3.5 CHARACTERIZATION OF STRUCTURE AND COMPOSITION

Samples of all materials used in the matrix and composites were made available for characterization. Some of these samples were ground to powdered form with the aid of a Pauline mortar and pistol, while others were crushed to smaller sizes as the characterization equipment and procedures required. The combination of scanning electron microscopy (SEM), energy dispersion spectroscopy (EDS) and X-ray diffraction (XRD) was used respectively to study the morphology, composition and structure of the materials.

SEM, EDS and XRD were carried out at the Sheddah Science Complex in Gwagwalada, Abuja, Nigeria. The SEM/EDS analysis was carried out in a Zeiss Evo 60 Environmental Scanning Electron Microscope (Carl Zeiss Canada Ltd., Canada) equipped with a Bruker AXS Quantax 4010 Energy dispersive X-ray Spectrometer (EDS). This was done on manually crushed samples. similarly, the XRD analyses was performed on crushed powdered samples that were ground and sieved through a 270 mesh sieve, before mounting them and characterizing in a MD-10 precision mini X-ray diffraction system (Radicon, Russia).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 STRUCTURE OF MATERIALS/CONSTITUENTS

The XRD and EDS patterns obtained are presented below in Figures 4.00 and 4.04. The laterite consisted predominantly of potassium aluminum silicate hydroxide $KAl_2(Si_3Al)O_{10}(OH_2)$ –illite.

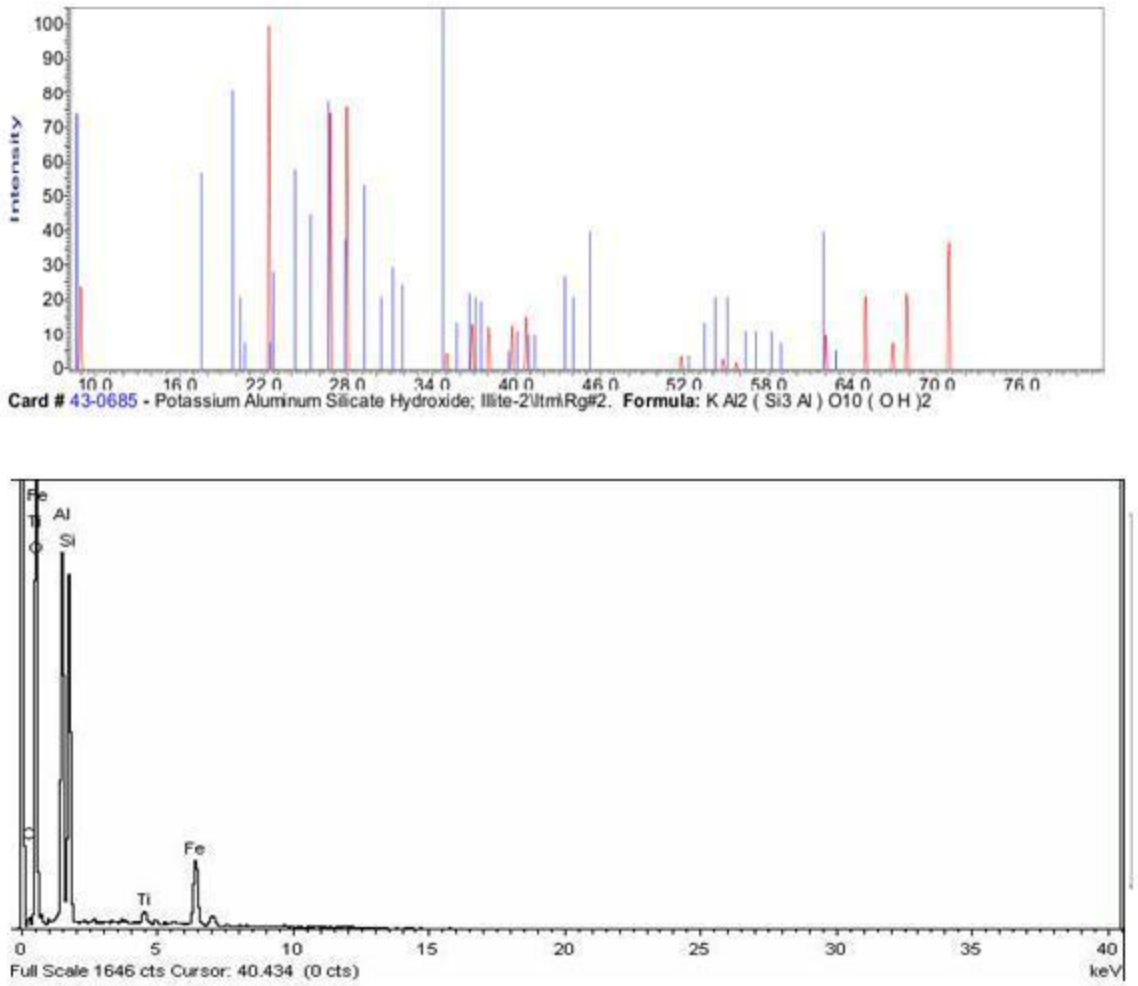
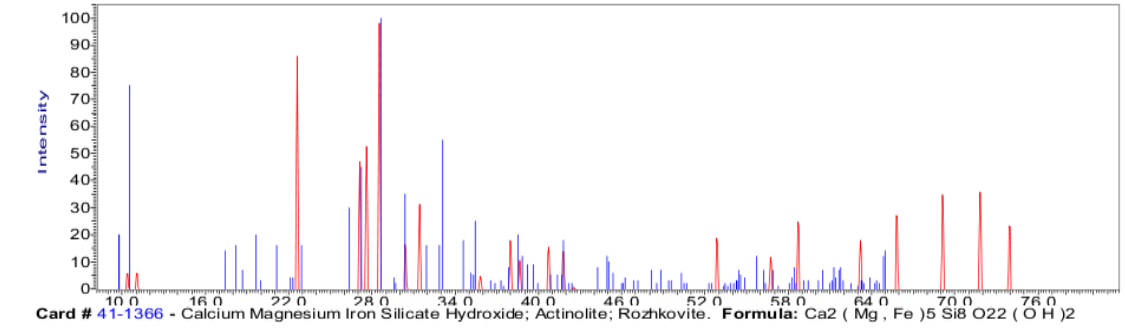


Fig. 4.00: XRD and EDS analysis of 100% laterite samples



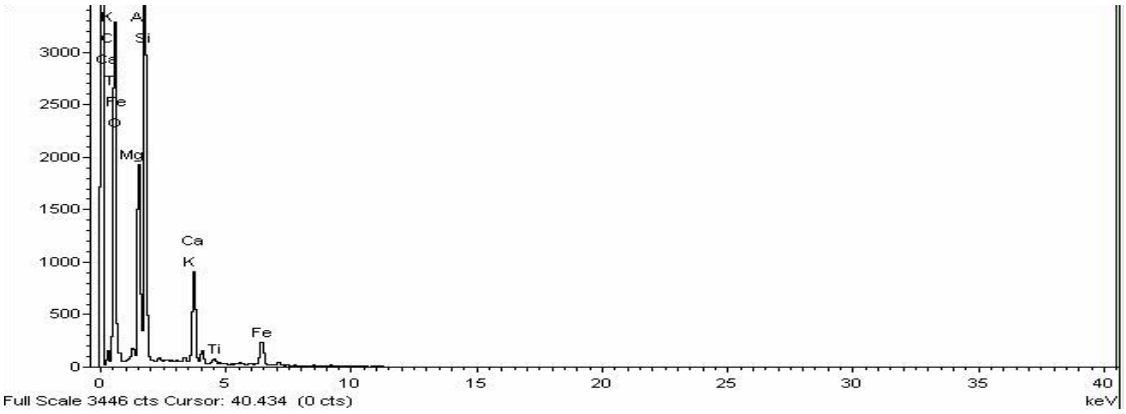
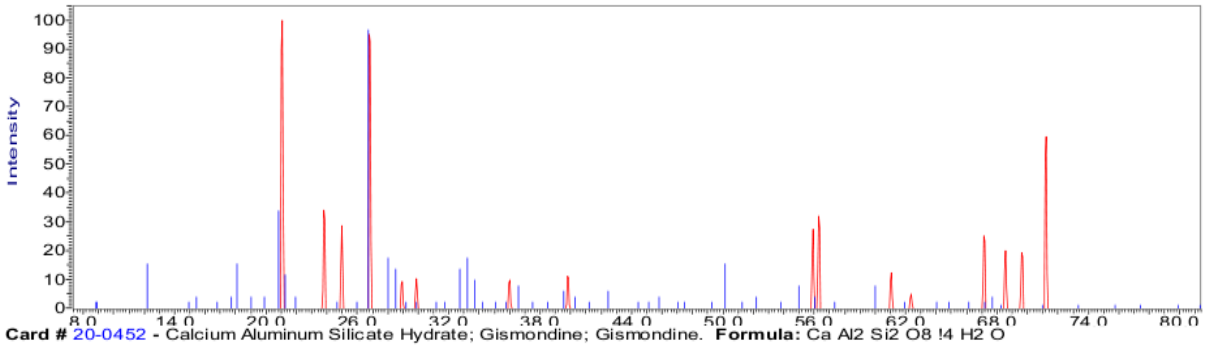


Fig. 4.01: XRD and EDS analysis of laterite + Cement samples



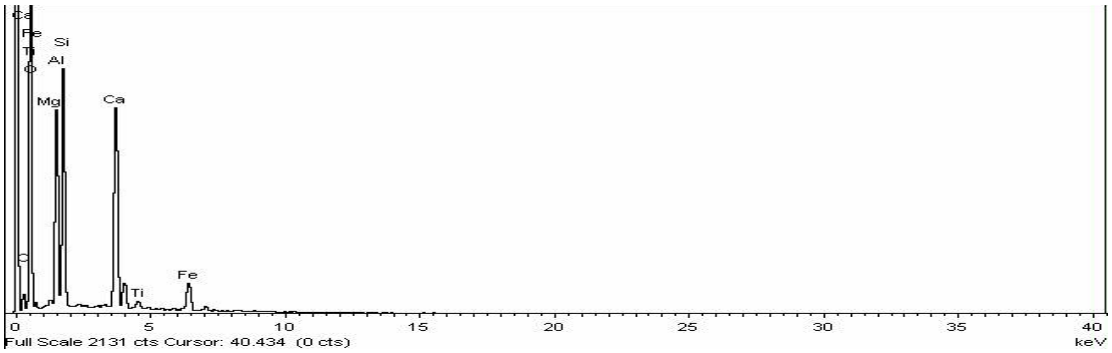


Fig. 4.02: XRD and EDS analysis of laterite + Clay + Cement samples

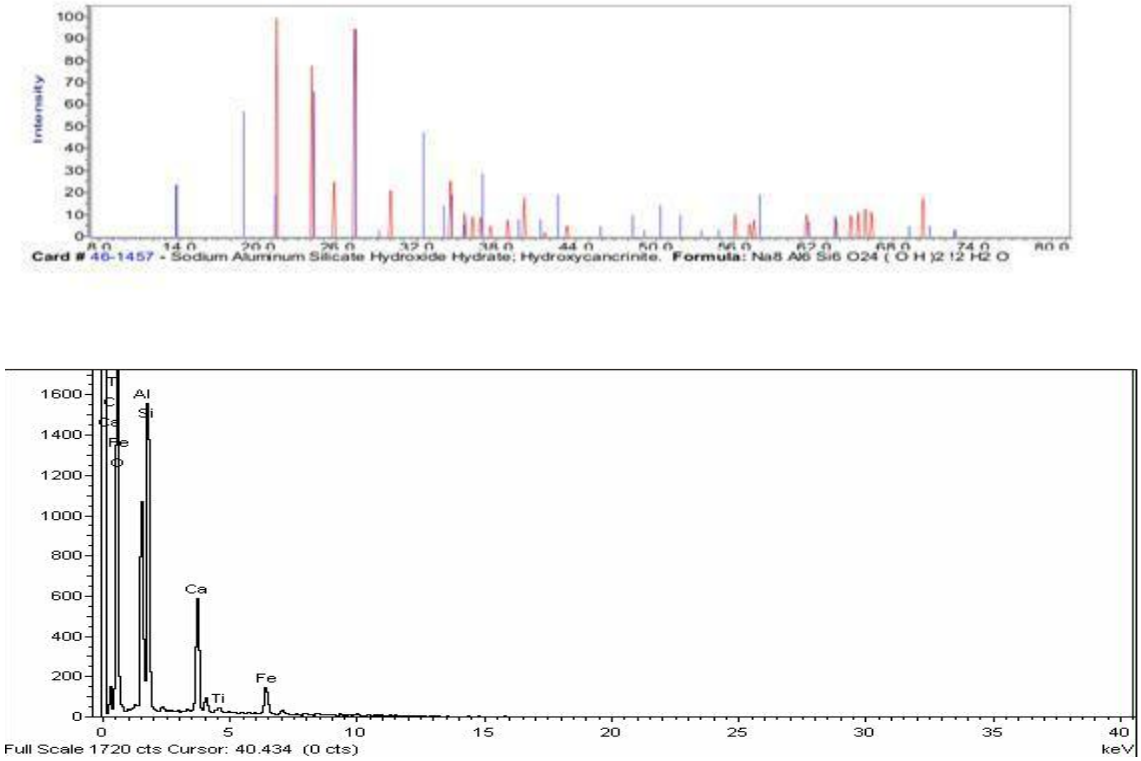


Fig. 4.03: XRD and EDS analysis of Matrix (L-C) + Fibre samples

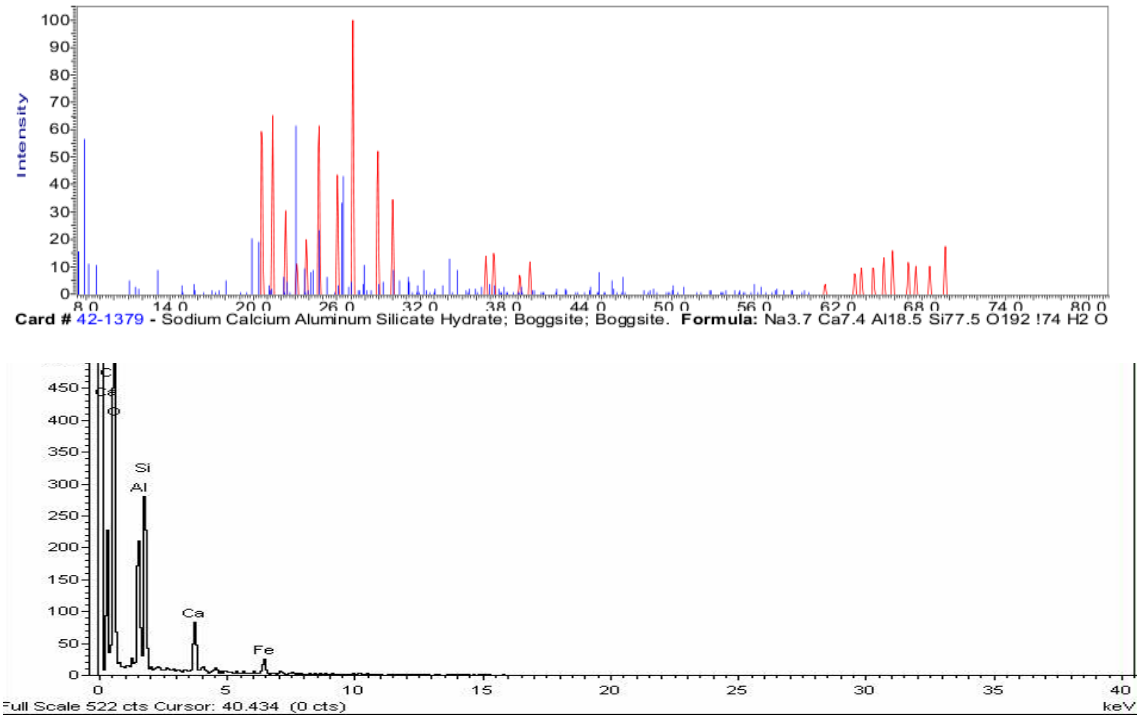


Fig. 4.04: XRD and EDS analysis of Matrix (L-C-C) + Fibre samples

The X-ray diffraction and energy dispersion spectroscopy analyses of the samples show the elemental compositions in the various matrices and composites. For pure laterite samples, XRD analysis showed elemental composition of potassium (K), aluminum (Al), Silicon (Si), oxygen (O) and hydroxyl (OH). From the EDS analysis, an additional element, Iron (Fe) was detected. The high strength and fracture toughness of this sample could be linked to the possible reactions between the elements detected. The result of such reactions may include SiO_2 Fe_2O_3 and Al_2O_3.

The introduction of cement into the matrix resulted in additional elements- calcium (Ca) and titanium (Ti). This is expected to induce more reactions in the matrix to enhance strength and toughness. Such reaction is expected to produce TiO_2, CaO and $CaSiO_3$. The addition of clay to the matrix did not result in additional elements. Although elemental composition is expected to be increased if a quantitative analysis is carried out. Also, the XRD and EDS analysis of the fiber reinforced composite samples did not reveal any significant differences in the elemental compositions compared to those in the unreinforced matrix.

4.2 SCANNING ELCTRON MICROSCOPY

The SEM images of the structure and morphology of the different samples are presented in Figures 4.05a-4.05e. These show the rough surface morphologies of the ground specimens. They also reveal the fiber morphologies in the fiber composite structures. The images of the composites show that the straw fibers were all bonded to the matrix materials. Such good bonding is consistent with the relatively high strengths of the straw fiber composites with fiber volume percentages of ~20%.

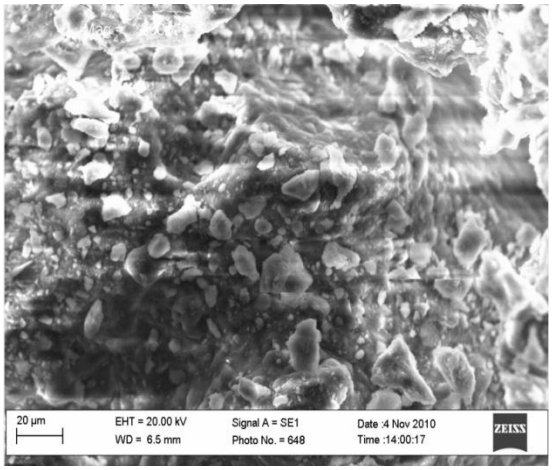


Fig. 4.05a: SEM micrograph of 100% Laterite (Mag. 100x)

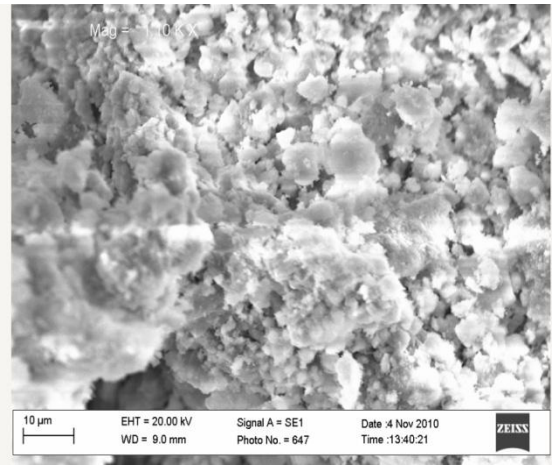


Fig. 4.05b: SEM micrograph of Laterite + Cement (Mag. 1100x)

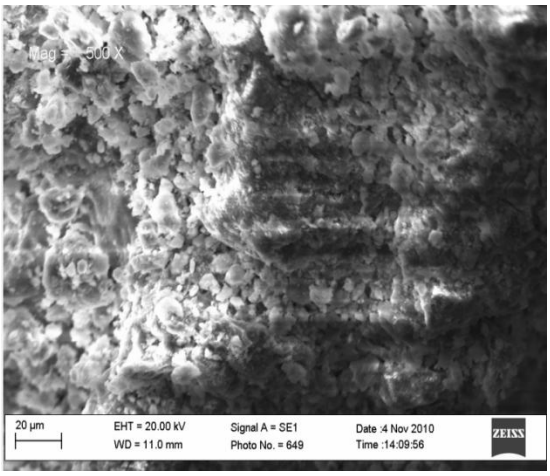


Fig. 4.05c: SEM micrograph of Laterite + Clay + Cement (Mag. 500x)

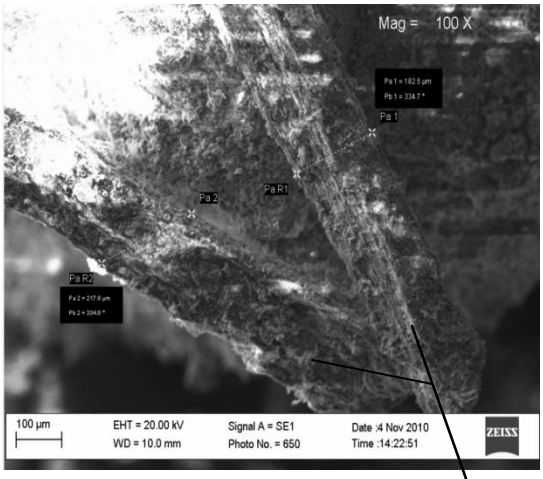


Fig. 4.05d: SEM micrograph Matrix (L-C) + Fibre (Mag. 100x)

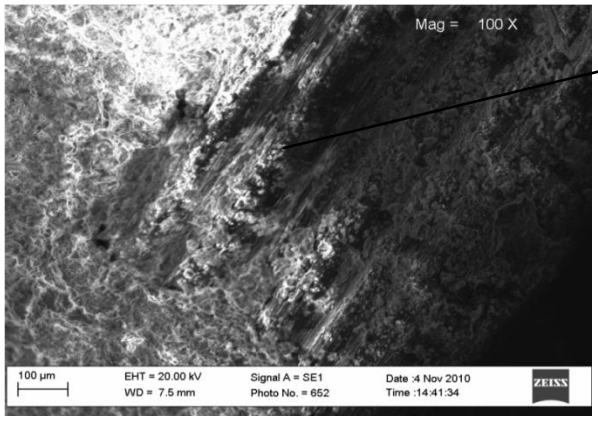


Fig. 4.05e: SEM micrograph Matrix (L-C- C) + Fibre (Mag. 100x)

4.3 COMPRESSIVE STRENGTH

Tables.4.00 and 4.01 summarize the compressive strengths of the matrix materials and the composites that were testes after 28 days. The trends in the data are also presented in Figures 4.06 and 4.07 for the matrix materials and composites.

Samples	Matrix composition	Maximum load (kN)	Area (cm^2)	Compressive stress (MPa)
A	100% L	1.27	4.17	3.03
B	95% L + 5% Ct	0.49	4.76	1.03
C	90% L + 10% Ct	0.91	4.88	1.87
D	80% L + 20% Ct	0.64	5.58	1.15
E	70% L + 10% Cy + 20% Ct	1.32	5.11	2.57
F	60% L + 20% Cy + 20% Ct	0.69	4.66	1.48
G	50% L + 30% Cy + 20% Ct	1.22	4.73	2.56
H	FIRED CLAY	1.59	3.21	4.95

Table 4.00: Compressive strength results for different matrices

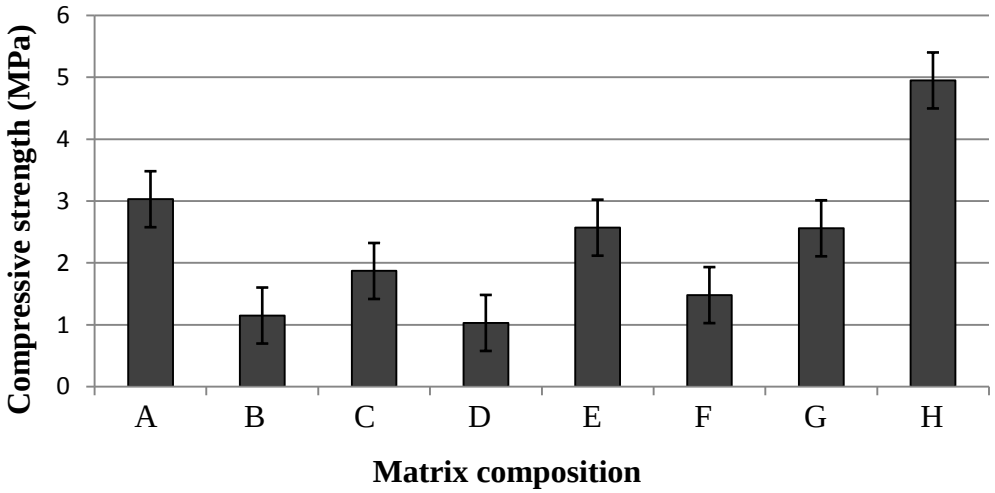


Fig. 4.06: Variation in compressive strength with different matrix compositions

Samples	composites	Maximum load (kN)	Area (cm^2)	Compressive stress (MPa)
I	95% Matrix (L-Ct) + 5% Fibre	0.96	5.05	1.90
J	90% Matrix (L-Ct) + 10% Fibre	0.96	4.68	2.06
K	80% Matrix (L-Ct) + 20% Fibre	1.38	5.55	2.48
L	95% Matrix (L-Cy-Ct) + 5% Fibre	0.79	4.89	1.61
M	90% Matrix (L-Cy-Ct) + 10% Fibre	0.95	5.06	1.87
N	80% Matrix (L-Cy-Ct) + 20% Fibre	1.26	4.35	2.91

Table 4.01: Compressive strength results for different composites

L ⇒ Laterites Cy ⇒ Clay Ct ⇒ Cement

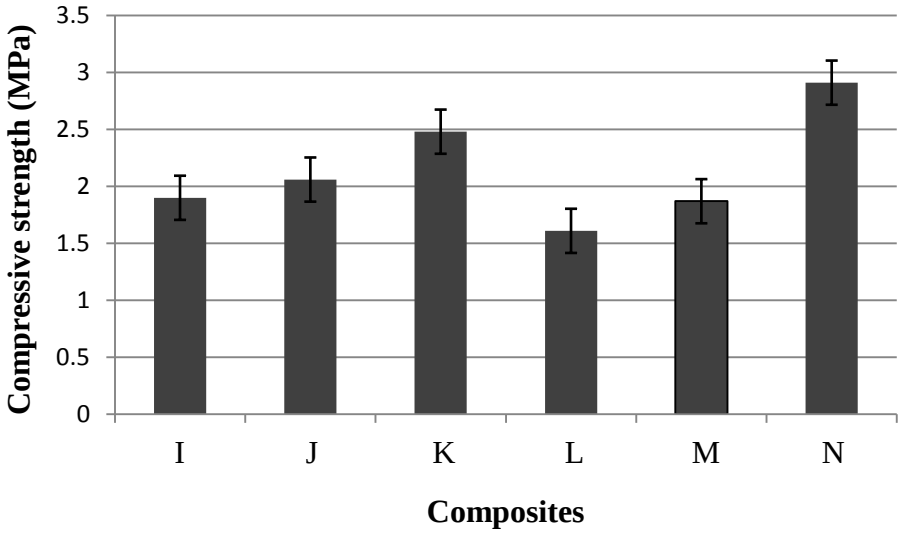


Fig. 4.07: Variation in compressive strength with different composites

The results show that the compressive strengths are increased with high fiber volume fraction of ~20 vol %. Also, for fiber volume fraction (~10%), there were no observable differences in the comprehensive strengths of the composites and those of the matrix materials. Hence, for high fiber contents (~20 vol %), the compressive strength was as

high as 2.91 MPa (about twice the value obtained for plain matrices except for those containing clay). The results also show that clay inclusion in the matrices and composites contributed to compressive strength enhancement.

Most interesting in these test results was that of the compressive strength of 100% laterite samples which stood out uniquely. It provided a compressive strength of 3.03 MPa, a value above those of the reinforced matrix and the closest to that of the fired clay (compressive strength of 4.95 MPa).

4.4 FLEXURAL STRENGTH

The results of the flexural tests are shown in Tables 4.02 and 4.03. All samples used for the tests are dimensionally the same.

Samples	Matrix composition	Maximum load (kN)	Bending moment (Nm)	Flexural stress (MPa)
A	100% L	0.97	19.5	28.6 ± 1.7
B	95% L + 5% Ct	0.90	18.0	26.5 ± 2.1
C	90% L + 10% Ct	0.86	17.2	25.3 ± 1.2
D	80% L + 20% Ct	0.80	16.0	23.5 ± 1.3
E	70% L + 10% Cy + 20% Ct	0.88	17.6	25.9 ± 2.4
F	60% L + 20% Cy + 20% Ct	0.78	15.7	23.0 ± 1.3
G	50% L + 30% Cy + 20% Ct	0.64	12.8	18.8 ± 1.5
H	FIRED CLAY	1.79	35.8	52.6 ± 2.2

Table 4.02: Flexural strength results for different matrices

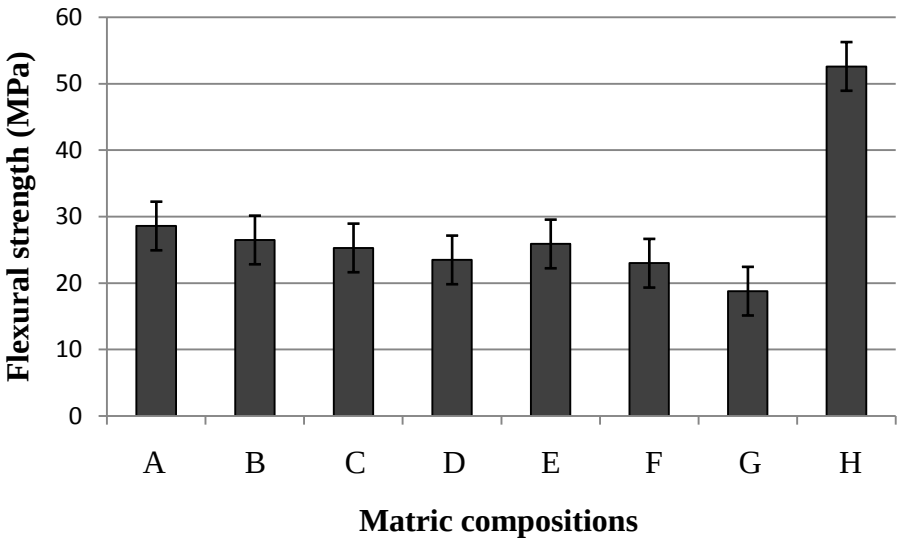


Fig. 4.08: Variation in flexural strength with different matrix compositions

Samples	composites	Maximum load (kN)	Bending moment (Nm)	Flexural stress (MPa)
I	95% Matrix (L-Ct) + 5% Fibre	0.70	13.9	20.5 ± 1.8
J	90% Matrix (L-Ct) + 10% Fibre	0.87	17.3	25.5 ± 1.3
K	80% Matrix (L-Ct) + 20% Fibre	1.07	21.5	31.5 ± 1.4
L	95% Matrix (L-Cy-Ct) + 5% Fibre	1.04	20.8	30.6 ± 2.0
M	90% Matrix (L-Cy-Ct) + 10% Fibre	1.07	21.3	31.4 ± 1.9
N	80% Matrix (L-Cy-Ct) + 20% Fibre	1.17	23.4	34.4 ± 1.5

Table 4.03: Flexural strength results for different composites

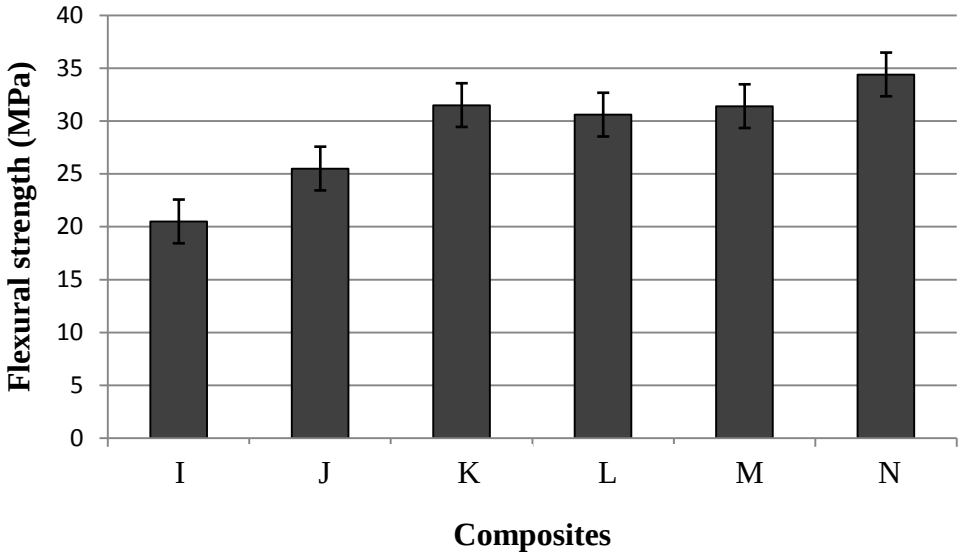


Fig. 4.09: Variation in flexural strength with different composites

At a content of 20% by volume, the fiber reinforcement studied provided a considerable increase in flexural strength relative to that of the unreinforced matrix after 48 days (see Figures 4.08 and 4.09). Flexural strengths observed at fibre content of 5% were not significantly different from those at 10%. However, the effect of introducing clay into the matrix was very evident in the results.

Furthermore, the results obtained are in agreement with those previously obtained by Savastano et al., 2000 (The use of Brazilian waste fibres as reinforcement). The increase in the flexural strength of the reinforced matrix relative to the plain matrix may be attributed to a considerable fibre-matrix bonding.

4. 5 FRACTURE TOUGHNESS

The results of the fracture toughness tests are presented in tables 4.02 and 4.03. The trends in the fracture toughness data are also shown in Figures 4.10 and 4.11.

Samples	Matrix composition	Maximum load (kN)	Bending moment (Nm)	Flexural stress (MPa)	Fracture toughness (MPa$\sqrt{m}$)
A	100% L	0.14	2.78	4.09	1.21 ± 0.07
B	95% L + 5% Ct	0.13	2.50	3.68	1.08 ± 0.01
C	90% L + 10% Ct	0.12	2.42	3.56	1.05 ± 0.04
D	80% L + 20% Ct	0.11	2.32	3.41	1.01 ± 0.03
E	70% L + 10% Cy + 20% Ct	0.11	2.22	3.26	0.96 ± 0.09
F	60% L + 20% Cy + 20% Ct	0.12	2.46	3.62	1.07 ± 0.06
G	50% L + 30% Cy + 20% Ct	0.13	2.50	3.68	1.08 ± 0.04
H	FIRED CLAY	0.23	4.60	6.76	2.00 ± 0.12

Table 4.04: Fracture toughness data for Different Matrix Materials

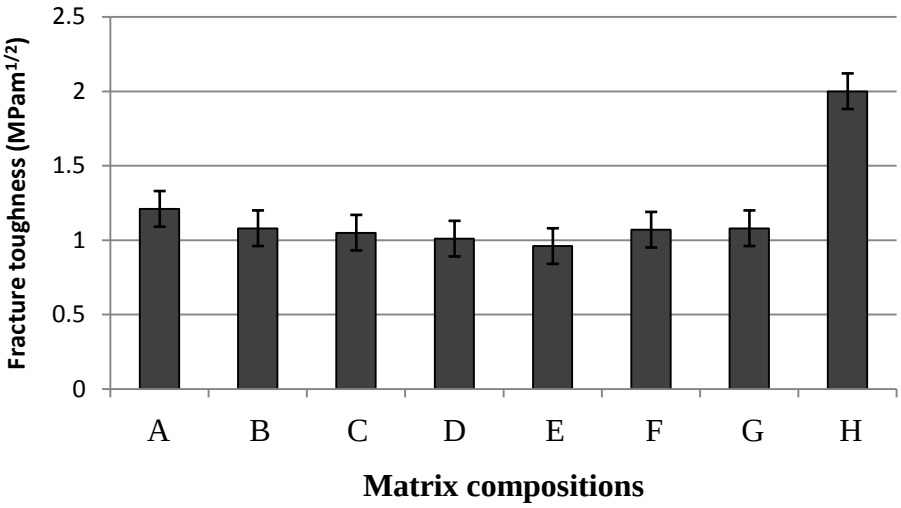


Fig. 4.10: Fracture Toughness data for Different Matrix Materials

Samples	composites	Maximum load (kN)	Bending moment (Nm)	Flexural stress (MPa)	Fracture toughness (MPa$\sqrt{m}$)
I	95% Matrix (L-Ct) + 5% Fibre	0.121	2.42	3.56	1.05 ± 0.14
J	90% Matrix (L-Ct) + 10% Fibre	0.135	2.70	3.97	1.17 ± 0.10
K	80% Matrix (L-Ct) + 20% Fibre	0.154	3.08	4.53	1.34 ± 0.11
L	95% Matrix (L-Cy-Ct) + 5% Fibre	0.142	2.84	4.17	1.23 ± 0.09
M	90% Matrix (L-Cy-Ct) + 10% Fibre	0.147	2.94	4.32	1.28 ± 0.12
N	80% Matrix (L-Cy-Ct) + 20% Fibre	0.162	3.24	4.76	1.41 ± 0.13

Table 4.05: Fracture toughness results for different composites

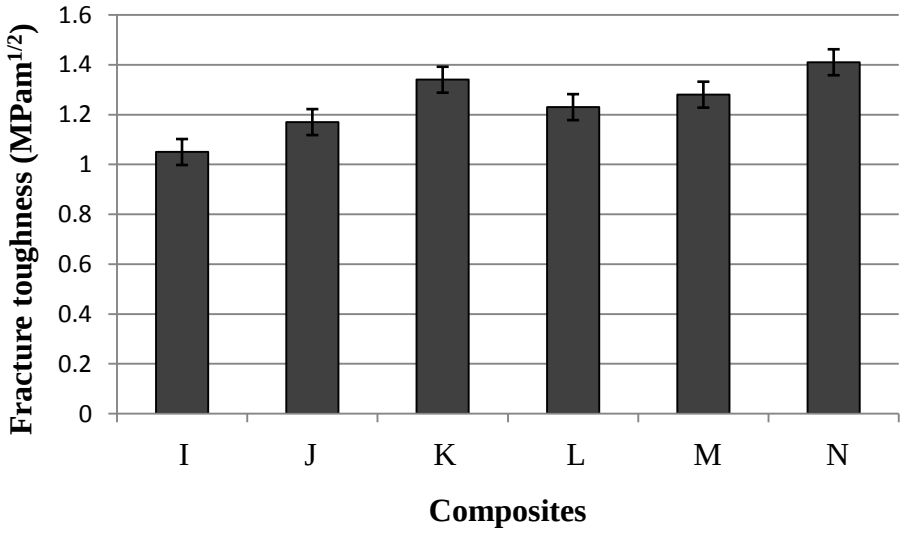


Fig. 4.11: Variation in fracture toughness with different composites

The fracture toughness of the plain samples was significantly enhanced by fiber reinforcement. At fibre contents of 20% by volume, the fracture toughness values far exceeded 1.0 MPa$\sqrt{m}$ (average value obtained for plain matrices). These results also

represent an improvement over those previously obtained by Savastano (Savastano et al., 1999 and 2000) and Agopyan (Agopyan, 1992) whose studies used vegetable fibers to obtain fracture toughness values between 0.5 MPa$\sqrt{m}$ and 1.0 MPa$\sqrt{m}$. Figure 4.11 shows the variations in fracture toughness values with different fibre compositions. The increase in fracture toughness attained as a result of fiber-reinforcement can be attributed to the shielding of the remote loads by bridging fibers (Budiansky et al., 1988). Debonding can also take place at the interface between the matrix and the fiber. This may result in considerable frictional energy losses that can contribute to the fracture toughness (Coutts, 1986).

4.6 IMPLICATIONS OF THE CURRENT WORK FOR AFFORDABLE HOUSING

In recent years, focus has been on the development of natural fiber-reinforced cementitious composites for affordable housing. This work had shown an improvement in the mechanical properties of earth-based materials when they are reinforced with natural fiber. Hence, it will provided a cost effective source of building materials since the amount of cement required is reduced.

In addition, reduction in the amount of cement needed for building will bring about a decrease in the amount of CO_2 emissions (thought to contribute to global warming) believed to originate from cement-based building materials.

CHAPTER FIVE

5.0 CONCLUSIONS AND FUTURE WORK

5.1 CONCLUSIONS

Composites consisting of earth-based materials reinforced with natural fiber (straw), and plain matrices were prepared. The mechanical properties of the various compositions (in both matrices and composites) were determined. The results in both cases were compared to verify the effects of reinforcement. The mechanical properties were determined with the aid of a universal testing machine. In addition, the results obtained were compared to that of fired clay. Scanning electron microscopy was used to characterize the surface morphology of the prepared samples. X-ray diffraction and energy dispersive X-ray spectroscopy were carried out to provide information on the structure and compositions of the samples.

Fiber-reinforcement resulted in an increase in compressive strength from 2.57 MPa to 2.91 MPa at maximum compressive strength. Interestingly, a plain laterite sample had a compressive strength of ~3.03 MPa. This value was the closest to that of fired clay (4.95 MPa). Samples reinforced with straw fibres had increased flexural strengths and fracture toughness. Composites with fiber volume percentage of ~20% had flexural strengths and fracture toughness values up to 34.4 ± 1.5 MPa and 1.41 ± 0.13 MPa$\sqrt{m}$ respectively. These values exceed those obtained for plain matrices (25.9 ± 2.4 MPa and 1.08 ± 0.04 MPa$\sqrt{m}$) at the same fibre composition.

The measured matrix strengths are consistent with reactions that are revealed by the XRD analyses. Similarly, the composite strengths are consistent with the good bonding between the straw fibers and the matrix materials.

5.2 SUGGESTIONS FOR FUTURE WORK

a) There is a need to study the underlying toughening mechanism and resistance-curve behavior of the different materials using techniques that are similar to those used in prior work on natural fiber-reinforced cementitious matrix composites (Savasrano et at., 2003). There is also a need to model the resistance-curve behavior using crack-tip shielding concepts.

b) There is the potential to extend the current work to materials produced from black cotton soil and bentonitic rocks. Other natural fibers could also be studied to provide a range of composite materials for potential applications in affordable buildings.

c) There is the need to study the potential degradation in the mechanical properties as a function of environmental exposure and cyclic loading.

REFERENCES

A. Schiesser et al., (1989): "Fine structure and Mechanical properties of Straw Filaments". Biological Wastes 27, 87-100.

Agopyan V, John VM. Durability evaluation of vegetable fibre reinforced materials. Build Res Infor, 1992; 20(4):233-5.

Banthia N, Sheng J. Fracture toughness of micro-fibre reinforced cement composites. Cement & Concrete Composites 1996; 18(4):251-69.

Bear and Johnston (2006). Mechanics of materials (5th ed.). McGraw Hill.

C. B. Ponton and R. D. Rawlings (1989),"Dependence of the Vickers indentation fracture toughness on the surface crack length", Br. Ceramics Trans.

Callister, W. D. (2007) Material Science and Engineering: An Introduction. 7th ed. John Wiley, New York.

Coutts RSP. Sticks and stones…!!. Forest Product Newsletter, CSIRO Div Chem Wood Technol 1986; 2(1):1-4.

Dieter, G. E. (1986) Mechanical Metallurgy. 3rd ed. McGraw-Hill, New York.

E. E. Gdoutos (2005), Fracture Mechanics: An Introduction, Second edition, Springer, Netherlands.

Budiansky B, Amazigo JC, Evans AG. Small scale crack bridging and the fracture toughness of particulate-reinforced ceramics. J Mesh Phys Solids 1988; 36(2):167-87.

F. Zok and C.L. Hom (1990): Acta Metall., Mater., vol. 38(10), pp. 1895-1904.

Grace, Hanry (1991). "Investigation in Kenya and Malawi using as-dug laterite as bases for bituminous surfaced roads". Journal Geotechnical and Geological Engineering. Springer Netherland.

Guggenheim, Stephen and Martin, R.T. (1995). "Definition of clay and clay mineral: Journal report of the AIPEA nomenclature and CMS nomenclature committees", clay and clay minerals 43:255-256.

Hibbeler, R.C. (2004) "Statics and Mechanics of Materials", S.I Edition, Prentice-hall.

Hillier, S. (2003), "Clay Mineralogy. In: Encyclopedia of sediments and sedimentary rocks". Kluwer Academic Publishers, Dordrecht. pp 139-142.

John VM, Zordan, SE. Research and development methodology for recycling residues as building materials –a proposal. Waste Mgmt 2001;21:213-9.

M. Bannister, H. Shercliff, G. Bao, F. Zok and M.F. Ashby (1992): Acta Metall. Meter., vol. 40(7), pp. 1531-37.

Moore, D. and R.C. Reynolds, Jr., 1997, X-Ray Diffraction and the Identification and Analysis of Clay Minerals, 2nd ed.: Oxford University Press, New York.

Nelson PK, Li VC, Kamada T. fracture toughness of microfibre reinforced cement composites. J Mater Civ Eng 2002; 14(5):384-91.

Nester Perez (2004), Fracture Mechanics, Kluwer Academic Publishers, Boston.

Sanjay, K. Mazumdar (2002),"Composites manufacturing; Materials, Products and Process Engineering", CRC press LLC.

Savastano Jr H, Warden PG, Coutts RSP. Brazilian waste fibres as reinforecement for cement based composites. Cement & Concrete Composites 2000; 22(5):379-84.

Savastano Jr H, Agopyan V. Transition zone studies of vegetable fibre-cement paste composites. Cem Concr Compos 1999; 21(1):49-57.

Savastano Jr H, Warden PG, Coutts RSP. Ground iron blast furnace slag as a matrix for cellulose-cement materials. Cement & Concrete Composites 2001; 23(4-5):389-97.

Savastano Jr H, Warden PG, Coutts RSP. Performance of low-cost vegetable fibre-cement composites under weathering. In: Duncan J, editor. Proceedings of the CIB World building Congress. Branz: Wellington; 2001. p. 11.

Savastano Jr H, Warden PG, Coutts RSP. Potential of alternative fibre cements as building materials for developing areas. Cement & Concrete Composites 2003; 27(5):585-92.

Savastano Jr H, S.F. Santos, M. Radonjic, W.O. Soboyejo. Fracture and fatigue of natural fiber-reinforced cementitious composites. Cement & Concrete Composites 2009; 31(5):232-43.

T. Fett and D. Munz: Stress Intensity factors and Weighing Functions for One-Dimensional Cracks, Institute for Materialforschung: Kernforshungszentrum, Karlsruhe, Germany, 1994.

Tardy, Yues (1997): Petrology of laterites and tropical soils. ISBN 90-5410-678-6.

Thurston, Edgar (1913): The Mandras Presidency, with Mysore, Coorg and the associated states, Provincial Geographic of India. Cambridge University press.

Timoshenko, S. (1976) "Strength of materials". 3rd edition. Krieger Publishing company.

Wood, R.B. and Macatamney, C.F. (1996). "Constructed waste lands for waste water treatments: The use of laterite in the bed medium in phosphorous and heavy metal removal". Hydro biological, Springer Netherland.