# ASSESSMENT OF THE FEASIBILITY OF USING SISAL FIBER REINFORCED CEMENT MORTAR WITH TERMITE CLAY SOIL FOR ROOFING TILES

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**Assessment of the feasibility of using sisal fiber reinforced cement Mortar with termite clay soil for roofing tiles**

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**A thesis submitted in partial fulfillment of the requirement of the Degree of Master of Science in Construction Engineering and Management in the Jomo Kenyatta University of Agriculture and Technology**

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## DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as university Supervisors.

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# DEDICATION

This thesis is dedicated to my dear wife Betty and our sons, Peace, Glory and Blessing, for their support and motivation.

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# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **C** | Cement |
| **TCS** | Termite Clay Soil |
| **W/C** | Water cement ratio |
| **D** | Day |
| **CS** | Compressive strength |
| **FS** | Flexural strength |
| **SW** | Saturated weight |
| **DW** | Dry weight |
| **ABS** | Absorption |
| **IE** | Impact energy |
| **SF** | Sisal fiber |
| **SFR** | Sisal fiber reinforcement |
| **$N/mm^2$** | Newton per millimeter square |
| **FRCC** | Fiber reinforcement cement composite |
| **OPC** | Ordinary Portland cement |
| **C-S-H** | Calcium Silicate Hydrate |
| **$I_{rs}$** | Impact Residual Strength Ratio |
| **CoR** | Coefficient of restitution |
| **KS** | Kenya Standard |
| **EAS** | East African Standard |

**ABSTRACT**

There is need to provide alternative materials that are locally available, that can reverse the adverse environmental effects caused by excessive use of Portland cement. It is important to have materials with low energy demand and low cost. The overall objective of this research was to assess the suitability of sisal fiber reinforced cement mortar with termite clay soil partial replacement for cement for use in roofing tile for housing. Termite Clay Soil (TCS) was obtained from Nduru Village, Usigu Sub Location, Siaya County in Kenya. The TCS used in this research was uncalcined. Chemical analysis on TCS was carried out by use of Energy Dispersive X ray diffraction (EDXRD), which is an analytical technique for characterizing materials. The sum of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ was found to be 93%, which is greater than 70% required as stipulated by the ASTM C 618 (1980). The pH of TCS was determined using pH meter and found to be 5.21. TCS replacement levels of 0, 10, 20, 30 and 40% by weight of cement was carried out to determine setting times, compressive strength, flexural strength and absorption rate of the resulting blended cement, from which optimal replacement value was obtained. 10% optimal replacement level achieved was used to determine the engineering properties of mortar namely compressive strength, flexural strength and absorption with sisal fiber reinforcement (SFR) of 0, 0.5, 1.0, 1.5 and 2.0% by weight of cement and fiber length of 25mm. Other studies have established that 25 mm length is optimal and this research adopted this length without further studies. The optimal replacement level for TCS was found

to be 10% for cement achieving compressive strength of 44.9 $N/mm^2$, flexural strength of 6.5 $N/mm^2$ and 6.5 % absorption rate which satisfied the requirement of KS EAS 18-1:2001 of minimum of 42.5 $N/mm^2$ for 42.5N Cement. Up to 2 % sisal fiber reinforcement satisfied the requirement of KS 02-444: 1984 of minimum 2.80 $N/mm^2$ for flexural strength and maximum 10% for absorption rate. Residual impact strength ratio ($I_{rs}$) of sisal fiber reinforced cement mortar with sisal fiber reinforcement for cement at percentages of 0, 0.5, 1.0, 1.5 and 2.0% increased with increase in reinforcement and at 2%, it yielded a value of 3.00. It was concluded that TCS was pozzolanic with the sum of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ equals to 93% and its pH was 5.21 which is acidic and therefore suitable for reducing the alkalinity of the cement matrix and hence reduction in embrittlement of sisal fibers. The optimal replacement of TCS was 10% for cement with up to 2% sisal fiber reinforcement for use in roofing tiles. Since $I_{rs}$ is closely related to Coefficient of restitution (CoR), this value satisfied the requirement of BS EN 14411: 2012, which recommends a minimum value of 0.55 for tiles intended for floors with low mechanical requirements. No standard was available that specifies the impact energy and impact residual strength ratio for roofing tiles and therefore this research adopted the standard for floors. From the cost analysis, cost per square meter of sisal fiber reinforced cement mortar with termite clay soil partial replacement tile was found to be Ksh 240, which is cheaper than other roofing materials which are in the range of 300 to Ksh 2000. There are also associated benefits which include: reduction of alkalinity of the cement media and therefore preservation of sisal fibers in the matrix; reduction in the emission of greenhouse gases by partial replacement of cement with the pozzolanic material and low energy consumption. Further studies are recommended on uncalcined termite clay soil as partial replacement for cement for use in roofing tiles.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background to the study

This research involves the use of sisal fiber as reinforcement in cement mortar with termite clay soil as partial replacement for cement for use in roofing tiles for housing. Therefore, it encompasses the use of mortar and it's also important to note in broad sense, the meaning of concrete and its keys weaknesses. Concrete, in the broadest sense, is any product or mass made by the use of a cementing medium. Generally, this medium is the product of reaction between hydraulic cement and water. It is a mixture of cement, water, aggregates (fine and course) and admixtures (Neville & Brooks, 1987). Concrete has limitations and certain disadvantages which should be realized by both the designer and the builder, since recognition of these characteristics will go far towards the elimination of costly difficulties in construction. The principal limitations and disadvantages are: low tensile strength and thermal movements. These temperature changes can cause severe strains and early cracking; drying shrinkage and moisture movement; Creep, concrete gradually deforms under load, the deformation due to creep not being wholly recoverable when the load is removed; permeability (Murdock, 1991).

Mortar is a binding material which can be made with Portland cement and blended cement. It is used in binding construction blocks. It can also be used for plastering and rendering purposes. The compressive strength of mortar is sometimes used as principal criterion for selecting mortar type, since it is relatively easy to measure and commonly relates to some other properties like tensile strength and water absorption (Olaniyi *et al.*, 2014). However, in this research cement mortar with termite clay soil as partial replacement for cement is used as material for roofing tiles for housing.

Considerable research has gone on in the field of fiber reinforced cement based materials, and the major advantage of fiber reinforcement is to impart additional energy absorbing capability and to transform a brittle material into pseudo ductile material. Fibers in cement or concrete serve as crack arrestor which can create a stage of slow crack propagation and gradual failure (Reynaldo, 2011). Sisal fiber reinforcement has been used in this research to acts as a crack arrestor and reduces crack propagation in roofing tiles. The need for sustainable, safe and secure shelter is an inherent global problem and numerous challenges remain in order to produce environmentally friendly construction products which are structurally safe and durable. The use of sisal, a natural fiber with enhanced mechanical performance as reinforcement in a cement based matrix has shown to be a promising opportunity (Flavio *et al.,* 2003).The natural fibers have been tried as reinforcement for cement matrices in developing countries. Vegetable fibers require only a low degree of industrialization for their processing and in comparison with an equivalent weight of synthetic reinforcing fibers; the energy required for their production is low. In addition the use of vegetable fiber in cement matrices requires only a small number of trained personnel in the construction industry (Yogesh, 2013). Thus, this research focused on using sisal fiber as reinforcement with termite clay soil as partial replacement for cement for use in roofing tiles for housing.

Pozzolanas are commonly used as an addition (chemical extender) to Portland cement concrete mixtures to increase the long-term strength and other material properties of Portland cement concrete, and in some cases to reduce the material cost of concrete. The extent of strength development depends upon the chemical composition of the pozzolana: the greater the alumina and silica along with the vitreous phase in the material, the better the pozzolanic reaction and strength display. Use of pozzolana can permit a decrease in the use of Portland cement when producing concrete; this is more environmentally friendly than limiting cementitious materials to Portland cement. As experience with using pozzolana has increased over the past 15 years, current practice may permit up to a 40 percent reduction in Portland cement used in the concrete mix when replaced with a carefully designed combination of approved pozzolana (Anigbogu, 2011). In this research uncalcined termite clay soil was used as a partial replacement for cement to reduce the use of Portland cement and improve durability of the sisal fibers in the matrix. The current practice for natural fiber reinforced composites is to partially replace Portland cement with a pozzolanic material (Sobral, 2004).

There is need for sustainable and environmental friendly materials in providing adequate housing for the teeming population of the world. These materials should be local and suitable as alternatives for the construction of functional buildings in both rural and urban areas (Raheem *et al.*, 2012).

Fibers have been used to toughen bricks and pottery since the very beginning of civilization, but fiber reinforcement of brittle matrices has only been done within the last thirty years. Fibers can be added to cement based matrices as primary or secondary reinforcement. Fibers work as primary reinforcement in thin products in which conventional reinforcing bars cannot be used. In these applications, the fibers act to increase both the strength and the toughness of the composite. In components such as slabs and pavements, fibers are added to control cracking induced by humidity or temperature variations and in these applications they work as secondary reinforcement (Yogesh, 2013).

Natural vegetable fibers which include cellulose pulp, sisal, bamboo, fique, hemp, flax, jute and ramie are used in regions where they are readily available. Motivations for their use include meeting the needs of sustainability and ecology. Composites with vegetable fibers are important for construction of inexpensive buildings in developing regions of the world. On the contrary, the use of synthetic fibers frequently involves higher costs and greater consumption of energy in the processing of fiber reinforced cementitious composites (Tonoli *et al.*, 2011). This research has applied the use of sisal fiber as reinforcement in cement mortar, primarily because sisal fiber is locally available; it's cheaper, lacks any health risk and is renewable.

The pile of earth made by termites resembling a small hill is called a termite mound. It is made of clay whose plasticity has further been improved by the secretion from the termites, while building the mound. It is therefore a better material than ordinary clay in terms of utilization for moulding. The clay from the termite mound is capable of maintaining a permanent shape after moulding. Termite mound clay has low thermal conductivity (Mijinyawa, 2007). However, in this study, termite clay soil was used as a pozzolanic material (Pozzolanic definition by ASTM C618 (1980) is a siliceous or siliceous and aluminous material which in itself, possesses little or no cementitious value but in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compound possessing cementitious properties. In this research, termite clay soil has been used as a pozzolanic material to serve two purposes, first is to act as partial replacement in cement and second to preserve the sisal fiber in the matrices since alkaline media courses embrittlement of sisal fibers. The Constitution of Kenya, (2010) in the Economic and social rights 43(1) recognizes housing as a social right for every Kenyan and the government should be committed to make sure that this is achieved progressively. For the Country to realize and provide this right, it is important for a new building code to be developed to cater for housing construction using locally available and environmentally friendly materials. Further, there should be a deliberate effort to promote these materials as opposed to conventional imported materials. Kenya GOK (2030) aims to transform the country into a newly industrializing, "middle income country providing a high quality of life to all its citizens by the year 2030". Use of local sustainable materials can make a great contribution.

## 1.2 Problem statement

The lack of housing is a critical problem not only in Kenya but also in many developing countries, as millions of houses are needed to provide decent homes for individual families. The rapid increase in population has contributed to this problem (Sobral, 2004).

This study pursues the use of local materials, in this case termite clay soil and sisal fiber, to produce sustainable roofing tiles for housing. 80% of residents in urban Kenya live in informal settlements which lack in sanitation, space, basic infrastructure and waste disposal systems (Vuluku *et al.,* 2014). The poor facilities in informal settlements in Kenya predispose slum inhabitants to particularly poor health, and consequently they suffer from a high incidence of communicable diseases such as tuberculosis, diarrhea and malaria (Oxfam GB, 2009).

Cement is the most widely used construction material throughout the world with an estimated consumption of about 2.86 billion tons of Portland cement per annum worldwide. Cement production is however harmful to the environment due to carbon dioxide emission. Approximately 0.8 tons of $CO_2$ is estimated to be released into the atmosphere per ton of cement produced. With the cement industry accounting for 5-8% of global $CO_2$ emission, the cement industry is the second largest producer of this greenhouse gas. $SO_3$ and $NO_2$ released as a result of Portland cement manufacture are also known to cause serious environmental problems such as greenhouse effect and acid rain. Reducing cement production while maintaining sustainable development has thus been an important issue in the development of construction materials (James *et al.*, 2014).

## 1.3 Objectives

### 1.3.1 General objective

To assess the suitability of sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement for use in roofing tiles for housing.

### 1.3.2 Specific Objectives

i. To determine the properties and optimal mix of termite clay soil as partial replacement in cement for use in roofing tiles for housing.

ii. To determine the properties and optimal mix of sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement for use in roofing tiles for housing.

iii. To undertake the cost-benefit analysis of sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement for use in roofing tiles for housing.

**1.4 Justification of the study**

The shelter situation in Kenya just like in most developing countries is such that housing demand far outstrips supply, particularly in urban areas. The shortage in housing is manifested by overcrowding and spread of slums and squatter settlements in urban and peri-urban areas. In the rural areas the challenge is that of poor quality housing. Kenya's urban housing demand is estimated at about 150,000 units with an estimated annual average supply of only 35,000 units while an estimated 300,000 housing units require to be improved annually in rural areas. If the factors that constrain housing production are not addressed, the current situation is likely to be sustained or worsen, (Matindi, 2008).

Kenya's population has been growing rapidly over the years, the country's population in 1999 was 28.7 million with urban population being 5.4 million, and by 2009, this population had grown to 38.6 million and 12.5 million in urban areas, this requires increase in housing units in urban areas. The government investment in the housing sector between 2009 and 2012 amounted to approximately Ksh 4.5 billion. This amount could only help develop 3000 housing units for the plan period assuming a cost of Ksh 1.5 million per unit (Kenya national housing survey, 2012/2013). In view of the above expositions, there is an urgent need in this country to use locally available materials in housing development to meet the growing demand, and the consistent effort should be sustainability and cost. This research attempts to address these issues through the use of supplementary cementitious materials as partial replacement in cement and sisal fiber as reinforcement in roofing tiles for housing. The need for adequate roofing in developing countries is a vital problem for so many people. The solution of this problem is often linked to the import of iron sheets. The increasing economic burden that many less developed countries have to carry makes it harder to meet vital needs, such as roofing, by means of import. The efforts to find appropriate solutions based on locally available raw materials have thus become more and more important. The cost of conventional materials is too high; a considerable amount of this cost is due to the price of energy for manufacturing and to transportation costs, some materials such as cement poses adverse environmental effect (Raheem, 2012). The current costs of corrugated iron sheets is Ksh 300, pre-painted sheets is Ksh 700, Slate stone tiles is Ksh 1500, Wooden tiles is Ksh 1800 and Stone coated steel tiles is Ksh 2000 per square meter. The dream of owning a house particularly for low-income and middle income families is becoming a difficult reality. It is necessary to adopt cost effective, innovative and environment friendly housing technologies for construction. Two case studies in India established that 22.68% of the construction cost, including material and labor cost can be saved by using low cost housing technologies in comparison with the traditional construction methods for roofing (Tam, 2011). This research, if successful is expected to reduce the high housing deficit by reducing the cost of roofing materials, which is a key component in construction of housing.

## 1.5 The scope and limitation

### 1.5.1 Scope of the study

i. Termite clay soil (TCS) is available in many counties in arid and semi-arid areas in Kenya but the sample used in this research was obtained from Nduru village, Majengo sub location in Siaya County. It is expected that TCS from other Counties have similar properties. For this research, only uncalcined TCS was used. It should be noted that calcined TCS could give different results. Other studies have shown that calcination of pozzolanic materials activates $SiO_2$, which was not in the scope and this also increases the energy consumption.

ii. Other studies have established that 25 mm length is optimal for fiber reinforcement which was adopted in this research without further studies on fiber length. As most systems with fiber embedment length greater or equal to 25mm failed by fiber fracture, this length can be suggested as a critical length for sisal fibers (Filho *et al.*, 1999).

iii. This research entailed treatment of samples at Day 2 and Day 28 only. It is a well-known fact that concrete attains optimal strength after 28 days of curing.

iv. Durability of the tile was not measured because it required longer conditions of exposure, which could not be done within the limited time available for this research.

### 1.5.2 Limitations

The limitations of this research were noted on the following areas;

i. Use of manual mechanical grinder for grinding the TCS made it difficult to achieve uniform fineness. The use of electronic grinder which was not available in the University could have made all samples uniformly fine.

# CHAPTER TWO

## LITERATURE REVIEW

This research makes the following assumptions:

i. Termite clay soil as partial replacement for cement attains an optimal design mix at which the properties of the composite make it suitable for use in roofing tiles.

ii. Sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement attains an optimal design mix at which the mechanical properties of the composite makes it suitable for use in roofing tiles.

iii. Sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement is feasible for use in roofing tiles.

### 2.1 Theories of fiber reinforcement

Mixture rule for strength: The law of mixtures for aligned continuous fibrous composites may be modified to predict the strength of natural fiber reinforced cements. It will be assumed that at failure, the fibers are broken but are pulled out of the cement matrix. ACK theory: In case of fibers reinforced cement and gypsum plaster, however, the matrix is brittle and fails at strain of the fibers and it is widely accepted that the tensile strength depends on the fiber contribution alone (Yongni, 1995).

### 2.2 Structure of fibers

The structure composed of reinforcing fibers or wires may be characterized by the following parameters: material of fibers; shape of the fiber; distribution of fibers in the matrix. The number of the above listed parameters indicates how many different types of reinforcing fibers structures may be used in concrete like composites. The reinforcement in the form of fibers or wires is by its nature subject to randomness in comparison with classical reinforcement by bars or pre-stressing cables which are very precisely positioned in the reinforced elements (Brandt, 1995).

### 2.2.1 Mechanics of crack formation and propagation

The main benefit of fibers is their ability to transfer stresses across a crack and consequently enhancing the toughness and ductility of the concrete as well as the absorption capacity under impact. Concrete is a heterogeneous material with pores and micro cracks caused by shrinkage and thermal strains, which have been restrained by coarse aggregates and boundary conditions. During loading, the matrix transfers part of the load to the fi-bers before macro cracks are initiated. Hence, it is theoretically possible to increase the strength of the material by adding fibers. Yet, for the relatively limited fiber volumes that usually are added to conventional concrete, the fiber reinforcement does not cause any pronounced improvement of strength. This is related to low tensile strain capacity of the cementitious matrix and also to the increased porosity that the fiber addition induce. Provided that fiber rupture is avoided, debonding between fiber and concrete starts on the shortest embedded lengths until full debonding occurs. The initial cracks will then start to grow and eventually lead to a macro crack which covers several cracks. The bridging of fibers across cracks provides a post crack tensile strength to the concrete. In addition to the debonding and fiber pull-out, other mechanics like matrix spalling and plastic defor-mation of the fiber might be present. Depending on the amount of fibers crossing the crack and on the fiber matrix bonding, the post crack stress can be larger than the crack-ing load resulting in strain hardening behavior where multiple cracking occurs. However for normal fibers dosages (<1%) the material exhibit strain softening behavior (Dossland, 2008).

## 2.3 Theories of pozzolanic reaction mechanism

Two major theories have been proposed to explain the mechanism of the lime-pozzolan reaction. The first and oldest theory proposed Base Exchange as the mechanism. Because of the glassy and foamy nature of the Italian pozzolans, pozzolans were thought to be ze-olites and Base Exchange was thought to be the mechanism. In Base Exchange, one basic ion or cation is exchanged for another by fitting into a similar position in the crystal lat-tice. The Base Exchange theory has been discredited by recent investigators for several reasons: Normal zeolites do not exhibit pozzolanic activity; complete removal of all bases by electro dialysis does not affect pozzolanic reaction and the amount of lime reacted is far more than can be accounted for by exchange reactions. The newer theory is that the reaction between pozzolan and lime is a surface reaction between dissolved lime and the solids of low solubility, with the formation of a solid resultant product. Increases in the amount of soluble silica and alumina in lime-pozzolan mixes indicate these materials re-acted with lime. Also, the fact that quartz and lime react at elevated temperatures and that burnt bauxite forms an excellent pozzolan, indicate that silica and alumina are probably the reactive fraction of pozzolans. Ferric oxide and sulfate compounds may react with lime to form compounds that increases cementation but these are considered secondary reactions (Leonard, 1958).

### 2.3.1 Pozzolanas

One of the common materials classified as cementitious is pozzolana which is natural or artificial material containing silica in a reactive form. A more formal definition of ASTM 618-88a describes pozzolana as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. It is essential that pozzolana be in a finely divided state as it is only then that the silica can combine with calcium hydroxide (produced by the hydrating Portland cement) in the presence of water to form stable calcium silicates which have cementitious properties. We should note that the silica has to be amorphous, that is, glassy, because crystalline silica has very low reactivity. The glass content can be determined by x-ray diffraction spectroscopy or by solution in hy-drochloric acid and potassium hydroxide. Broadly speaking, pozzolanic materials can be natural in origin or artificial. The natural pozzolanic materials most commonly met with are: volcanic ash-the original pozzolana-Pumicite, Opaline shales and Cherts, Calcined diatomaceous earth, and Burnt clay. ASTM C 618-08a describes these materials as class N. Some natural pozzolanas may create problems because of their physical properties eg diatomaceous earth, because of its angular and porous form, requires high water content. Certain natural pozzolanas improve their activity by calcination in the range of 550 to 1100˚C depending on the material.

For an assessment of pozzolanic activity with cement, ASTM C 311-07 prescribes the measurement of a strength activity index. This is established by the determination of strength of mortar with a specified replacement of cement by pozzolana. The outcome of the test is influenced by the cement used, especially its fineness and alkali content. There is also a pozzolanic activity index with lime which determines the total activity of pozzo-lana. The pozzolanicity of pozzolanic cements, that is, cements containing between 11 and 55 per cent of pozzolana and silica fume according to BS EN 197-1:2000, is tested according to BS EN 196-5:2005, the test compares the quantity of calcium hydroxide in an aqueous solution in contact with the hydrated pozzolanic cement, with the quantity of calcium hydroxide which saturates a solution of the same alkalinity. If the former concen-tration is lower than the latter, then the pozzolanicity of the cement is considered to be satisfactory. The underlying principle is that the pozzolanic activity consists of fixing of calcium hydroxide by the pozzolana so that the lower the resulting quantity of calcium hydroxide the higher the pozzolanicity. Pozzolanicity is still imperfectly understood; spe-cific surface and chemical composition are known to play an important role but, because they are inter-related, the problem is complex. It has been suggested that, in addition to reacting with $Ca\ (OH)_2$, pozzolanas also react with $C_3A$ or its products of hydration (Ne-ville,2011).

### 2.4 Cement based composites

The Fiber Reinforced Cement Composites (FRCC) have been widely used since the middle of the $20^{th}$ century and currently recognized as one of the most efficient and high performing materials for construction of slab and wall systems, manhole covers, roads, pavements and industrial floors, pipe works and tunnel lining, jacketing around columns. This is because FRCC provide combined properties of interest to civil engineering applications which include strength, toughness, energy absorption, durability, corrosion resistance, water tightness, appearance and constructability. The role of the fibers in cement mortar is not only to overcome the traditional weakness of inorganic cements, namely poor tensile strength and brittleness but also to improve the resistance to impact, blast, explosion and other forms of dynamic loads when large amounts of energy are suddenly imparted to the structure (Sakthivel *et al.*, 2012). This research attempts to address the issues of tensile weakness in tiles by reinforcing the roofing tiles with sisal fiber to reduce crack propagation.

The major advantage of fiber reinforcement is to impart additional energy absorbing capability and to transform a brittle material into pseudo ductile material. Fibers in cement or concrete serve as crack arrestor which can create a stage of slow crack propagation and gradual failure (Reynaldo, 2011). Knowledge of fiber properties is important for design purposes; fiber tensile strength is usually higher than the matrix strength and becomes influential in post-cracking (Romildo *et al.*, 1999).

### 2.4.1 Cement matrix, the key to composite stability

The main concern with natural fibers is of one long term strength and stability. Marked embrittlement of sisal fibers, for example embedded in thin roofing sheet exposed to a tropical climate has been observed within a period of months. The embrittlement is known to be caused directly by the alkaline environment of the cement system. There is also evidence, on the other hand, that natural fibers remain practically intact in carbonated concrete. Protective impregnation of the fibers with various chemical treatments have, however, been unable to prevent the chemical decomposition of the fiber components completely, and have resulted in poorer composite properties due to impairment of fiber tensile strength and the effects on fiber-matrix interfacial bond properties. Since fiber embrittlement is caused primarily by the high alkalinity of the cement system, the solution to the deterioration of the natural fibers lies in the matrix itself. Cement replacement materials such as fly ash, ground granulated blast furnace slag and micro-silica offer one of the best means of reducing alkalinity to sufficiently low levels to enable the fibers to contribute to composite strength for a long time (Sobral, 2004). This research has adopted the use of termite clay soil as partial replacement for cement to reduce the high alkaline cement matrix and therefore ensure the preservation of sisal fibers in the matrix.

### 2.4.2 Durability of concrete

Inadequate durability manifests itself by deterioration which can be due to either external or to internal causes within the concrete itself. The various actions can be physical, chemical, or mechanical. Mechanical damage is caused by impact, abrasion, erosion or cavitation. The chemical causes of deterioration include the alkali-silica and alkali-carbonate reactions. External chemical attack occurs mainly through the action of aggressive ions, such as chlorides, sulfates, or carbon dioxide, as well as many natural or industrial liquids and gases. The damaging action can be of various kinds and can be direct or indirect. Physical causes of deterioration include the effects of high temperature or of the differences in thermal expansion of aggregates and of the hardened cement paste (Neville, 1996). This is important in this research because the materials produced are expected to be durable and sustainable to reduce the high housing deficit among the poor.

### 2.4.3 Carbonation

Discussion of the behavior of concrete is generally based on the assumption that the ambient medium is air which does not react with hydrated cement paste. However, in reality, air contains $CO_2$ which, in the presence of moisture, reacts with hydrated cement; the actual agent is carbonic acid because gaseous $CO_2$ is not reactive. The action of $CO_2$ takes place even at small concentrations such as is present in rural air where the $CO_2$

content is about 0.03% by volume. Of the hydrates in cement paste, the one which react with $CO_2$ mostly is Calcium hydroxide (Ca $(OH)_2$) resulting in the production of calcium carbonate ($CaCO_3$) (Lagerblad, 2005). Carbonation increases the durability of natural fibers in cement matrix. Carbonation is the reaction of cement hydration products with carbon dioxide available in the air, that is, Ca $(OH)_2$ with $CO_2$ resulting in the formation of calcium carbonate ($CaCO_3$). Tests involving artificial carbonation of products with asbestos fibers have shown the formation of around 35-40% of $CaCO_3$, with the consequent increase of composite strength, reduction of specific energy and water absorption. A significant increase in durability of the composite was reported with 109 days of exposure to carbon dioxide air (Tonoli *et al.*, 2006). However, in this research, termite clay soil was used in place of carbonation to prevent embrittlement of sisal fibers in the cement matrix.

### 2.4.4 Cement and carbon dioxide formation

Cement is a defined chemical entity formed from predetermined ratios of reactants at fairly precise temperature. Ordinary Portland cement results from the calcination of limestone and silica is given in the following reaction:

$$\text{Limestone + Silica } (1450^0\text{C}) = \text{Portland cement + Carbon dioxide} \qquad (2.1)$$

$$5CaCO_3 + 2SiO_2 \rightarrow (3CaO.SiO_2)\ (2CaO.SiO_2) + 5CO_2$$

The production of one ton of cement produces 0.55 tons of chemical $CO_2$ in a reaction that takes place at 1450 degrees centigrade. An additional 0.4 tons of $CO_2$ is given as a result of the burning of carbon fuel to provide this heat (Davidovits, 1994). In this research termite clay soil is being used for partial replacement for cement to reduce the emission of carbon dioxide therefore this research is significant because it deals with solving the issue of overdependence on cement while at the same time trying to produce sustainable roofing tiles for housing.

**2.5 Termite clay soil**

In this research termite clay soil was used as a pozzolana, for partial replacement for cement for use in roofing tiles for housing. Large termite mounds, constructed by colonies of various species of *macro-termitine* (Isoptera, Termitidae, and Macrotermitinae) are dominant features of the arid and semi-arid areas. These mounds can populate a savanna in very high densities, generally one to four colonies per hectare containing biomass of termites and symbiotic fungi. Termites' construction of nest and mound turns over savanna soils at substantial rates; they convey significant quantities of inorganic matter into nests, concentrating it there. Some large soil invertebrates have significant effects on soil structural properties, the most important being earthworms, termites and ants. Through their actions, fungus-moving termites greatly modify their immediate environment by increasing the clay content and decreasing the organic matter content and porosity in soil. The proportion of clay in termite nests is always higher than in the bulk soil, often highest in the royal cell and lowest in the outer wall (Turner, 2006). The loose soil that had been brought to the surface and piled on the ground by ants during excavation of their nests weighed approximately 40 tons (Wirth *et al.,* 2013). Therefore a colony could approximately produce 40tons of soil. But they did not indicate how long it takes to make a colony. Termite clay is obtained from termite mound, while a mound is a pile of earth made by termite resembling a small hill. It is made of clay whose plasticity has further been improved by the secretion from the termite while using it in building the mound. The clay from the termite mound is capable of maintaining a permanent slope after molding because of its plasticity; it is also less prone to cracking when compared with ordinary clay (Mijinyawa, 2007).

Today, the high energy consumption by Portland cement industry causes environmental damage due to the release of high quantities of greenhouse gases. Hence, several research activities are directed towards partial or full substitution of Portland cement with the pozzolanic binder in some applications. In recent years, the use of calcined clays as pozzolanic materials for mortar and concrete has received considerable attention. American Society of Testing and Materials (ASTM) set a minimum value of 70% for the sum of silica, alumina, and iron oxide of the total compounds making up the pozzolanic material with sulfur dioxide less than 4% and loss of ignition of less than 10% (Wafa *et al.,* 2012). This interest is part of the widely spread attention directed towards the utilization of wastes and industrial by-products in order to minimize Portland cement consumption, the manufacture of which being environmentally damaging. Mortar and concrete, which contain pozzolanic materials exhibit considerable enhancement in durability properties (Chakchouk et al., 2006). Portland cement production has been traditionally involved in calcination of limestone and siliceous clay to produce clinker, which is then undergrounded with 3-5% gypsum. However, current trends in cement production involve the addition of 5- 70% mineral admixtures in order to improve the technical properties and durability of cement. The presence of admixtures like fly ash, limestone, slag and pozzolana in Portland cement influences the rate and degree of cement hydration as well as the phase composition of hydrated cement paste (Eugene *et al.,* 2014). In this research termite clay powder is used as a pozzolanic material to partially replace ordinary Portland cement. Pozzolans are natural rocks of volcanic origin and composed of silica and alumina oxides but almost no lime. Therefore, they cannot develop hydraulic properties in the absence of hydrated lime. Hydrated lime or material that can release it during its hydration (e.g Portland cement) is then required to activate the natural pozzolana as a binding material. Reactive silica is readily dissolved in the matrix as $Ca(OH)_2$ becomes available during the hydration process. These pozzolanic reactions lead to the formation of additional Calcium silicate hydrates (C-S-H) with binding properties (Alp *et al.,* 2009). In Kenya, termite clay soil is available in many parts of the countries, but they are more prominent in arid and semi-arid areas. This makes it more viable for use as partial replacement for cement.

## 2.6 Natural fiber reinforcement composites

In recent years, a great deal of interest has been created worldwide on the potential applications of natural fiber reinforced cement based composites. Investigations have been carried out in many countries on various mechanical properties, physical performance and durability of cement based matrices reinforced with naturally occurring fibers including sisal, jute, bamboo and wood. These fibers have always been considered promising as reinforcement of cement based matrices because of their availability, low cost and low consumption of energy. Fibers such as sisal, jute and coconut have been used as reinforcement of cementitious matrices in the form of short filament fibers. Short filament geometry composites presented a tension softening behavior with low tensile strength, resulting in products which are more suitable for non-structural applications (Suryawanshi, 2013).

### 2.6.1 Sisal

Sisal fiber is obtained from the leaves of the plant *Agave Sisalana* and is produced in the tropical regions such as Mexico, Brazil, Tanzania, Kenya, Madagascar and China. It is mainly used in the manufacturing of natural ropes, twine, sacking, carpet making and textile materials like nets, mats and automobile floor mats. Sisal fiber can be used as reinforcement in production of composites (Ewa *et al.,* 2013). Sen (2011), studied sisal fiber and found out that, it is a prospective reinforcing materials whose use has been more empirical up to 2011. His work was technical. He also studied the composition of sisal fiber as basically cellulose, lignin and hemicelluloses, and concluded that failure strength and the modulus of elasticity, besides the lengthening of rupture, depend on the amount of cellulose and the orientation of the micro-fibers.

In Kenya sisal is mainly produced by large scale plantations with long experience and knows how. Kenya produces the world’s best quality sisal fiber that is mainly used in the manufacture of high quality and premium products such as carpets, specialty paper, gypsum blocks, twine and composites. It is mainly grown at the Coast, Upper Eastern, Nyanza and parts of Central province. Over the last 10 years sisal production has had both growth and decline phases in production, there has been a steady increase in earnings from 2000-2007. Average production for the same period was 23,935 Metric tons with the highest production achieved in the year 2004 when 26,604 Metric tons of fiber was produced. Out of the production for the year 2004, the plantations produced 21,478 Metric tons which is 80% of total production while small holders produced 5,126 Metric tons approximately 20% of total production (Export processing zones authority, 2005). This is important in this research because sisal fiber is used as reinforcement in cement mortar for roofing tiles for housing, therefore competing uses and availability becomes a key issue for justification of its use in the country.

### 2.6.2 Sisal fiber reinforced cement based composites

The use of sisal, a natural fiber with enhanced mechanical performance as reinforcement in a cement based matrix has shown to be a promising opportunity. The cement matrices can consist of paste, mortar or concrete. Most of the studies on sisal fiber concrete involve the use of ordinary Portland cement. However, high alumina cement, cement with additives such as fly ash, slag, silica fume have also been used to improve the durability of the composites. Studies of sisal fiber reinforced concrete were started in Sweden in 1971. Cut fibers with a length of 10-30 mm were cast into beams and an improvement in the tensile strength was observed for fiber reinforced specimens. It was found that toughness increased markedly when continuous fiber was used. In 1977 the Building Research Unit (BRU) in Dar es Salaam started collaboration on the development of roof sheets on natural fiber reinforced concrete with the Swedish Cement and Concrete Research Institute. Test sheets were manufactured for durability experiments. A special roof sheet profile was developed and several buildings have been provided with sisal fiber reinforced concrete roofs. Their results on the flexural static strength and toughness of beams made of cement based matrices reinforced indicated that remarkably high strengths can be achieved using suitable mixing and casting techniques with optimum fiber volume fraction, although the modulus of rupture is found for different ages (Suryawanshi, 2013). Termite clay powder was used to reduce the alkalinity of the matrix and hence durability of the composite in this research.

### 2.6.3 Roofing sheets and tiles reinforced with vegetable fibers

Natural fibers as reinforcement of fragile matrices based on cementitious materials have provoked great interest in developing countries based on their low cost, availability, economy of energy and also as asbestos substitute regarding environmental concerns. The use of composites in flat sheets, roofing tiles and pre-manufactured components, can represent significant contribution for the infrastructure of these countries. Studies using compaction by vibration for production of roofing tiles reinforced with natural fibers observed losses of 50% average on mechanical performance after one year of natural exposure. Authors attributed the decrease in the mechanical performance to the degradation of vegetable fibers, which is accelerated by the alkaline media of the cement matrix (Tonoli *et al.*, 2006). The materials used in producing the tiles are Portland cement, sand, water and natural fibers. The basic mix is 1:3, cement: sand ratio with the addition of 1% sisal fiber by weight. It is important that fibers are flexible and not brittle; fibers should not be oily or contain substances such as sugar which affects the hydration of cement. It has been shown that the durability problems in the use of sisal fiber as reinforcement in tiles in various locations are due to alkali attack of the fibers by the pore water present in the cement matrix. Alkali attack on the fibers can be reduced by reducing the alkalinity of pore water and one method of doing so, is by replacing part of the cement with a pozzolanic material (Uzoegbo, 2011). Experience has shown that 300 tiles can be made per day, which consists of eight hours. A normal roof which in this case is 60 square meter might need 900 tiles, which is equivalent to three days of production (Johansson, 1995). He did not state the labor and equipment requirements in the construction of a normal roof. This research, studied sisal fiber reinforced cement mortar with termite clay soil as partial replacement for cement for use in roofing tiles for housing in Kenya.

### 2.6.4 Qualities of tiles

The section is important in this research because it provides the necessary standard and guidelines to be achieved in a roofing tile.

#### 2.6.4.1 Specification for concrete roofing tiles

Table 2.1 below gives the standard specifications for concrete roofing tiles. The different concrete tiles as outline in the table below are: plain and interlocking. For this research, the plain tile was adopted. The required standard for absorption in a concrete roofing tile is a maximum of 10 percent and therefore the tested specimen roofing tiles must fall within the limit to be considered feasible. The breaking load for individual tiles for concrete roofing tiles should be at least 2.80N per mm width, the specimen tiles to be considered feasible must be at least 2.80N per mm width.

**Table 2.1: Dimensions of concrete roofing tiles**

| Type & size | Nominal length(mm) | Nominal width(mm) | Thickness(mm),min | Side lap(mm), min |
|---|---|---|---|---|
| **Plain** | 265 | 165 | 10 | - |
| **Interlocking:** | | | 10,except in the interlocking portion that shall have a minimum thickness of 8 | |
| **Small** | 380 | 230 | | 25 |
| **Medium A** | 420 | 280 | | 25 |
| **Medium B** | 420 | 330 | | 25 |
| **Large** | 430 | 330 | | 25 |

**Source: KS 02-444: 1984**

The required specifications for tests for concrete roofing tiles include: water absorption, which requires that the average percentage for water absorption shall not be more than 10 percent; breaking load, the average breaking load of 10 tiles shall be at least 3.15N per mm width; and finally the individual breaking load of each tile of the 10 shall be at least 2.80N per mm width (KS 02-444: 1984).

#### 2.6.4.2 Specification for Portuguese clay roofing tiles

Table 2.2 below shows the specifications required for the Portuguese clay roofing tiles. For any test carried out on clay tiles, absorption and permeability are the key parameters required. However for this research, tests were carried out in accordance with the tests for concrete tiles.

**Table 2.2: Dimensions and weight of Portuguese roofing tile**

| Length(mm) | Width(mm) | Height (mm) | Weight per tile |
|---|---|---|---|
| **410** | 250 | 70 | 3 |

**Source: KS 431-5: 2006**

The basic requirements for portugueese roofing tile include: water absorption, which stipulates that the maximum water absorption of tiles shall be 14%; permeability, this requires that the tiles shall be tested for permeability and shall be considered as conforming to the test if no water is found dripping at the bottom of the tile after test (KS 431-5: 2006).

### 2.6.4.3 Current trend of tile usage in Kenya

The main kinds of roofing materials used in Kenya are: clay tiles, concrete tiles, stone coated steel sheets and galvanized iron sheets. There are also innovative iron sheets products under brand names like orientile (Ongeti, 2014).

## 2.7 Summary of the literature review

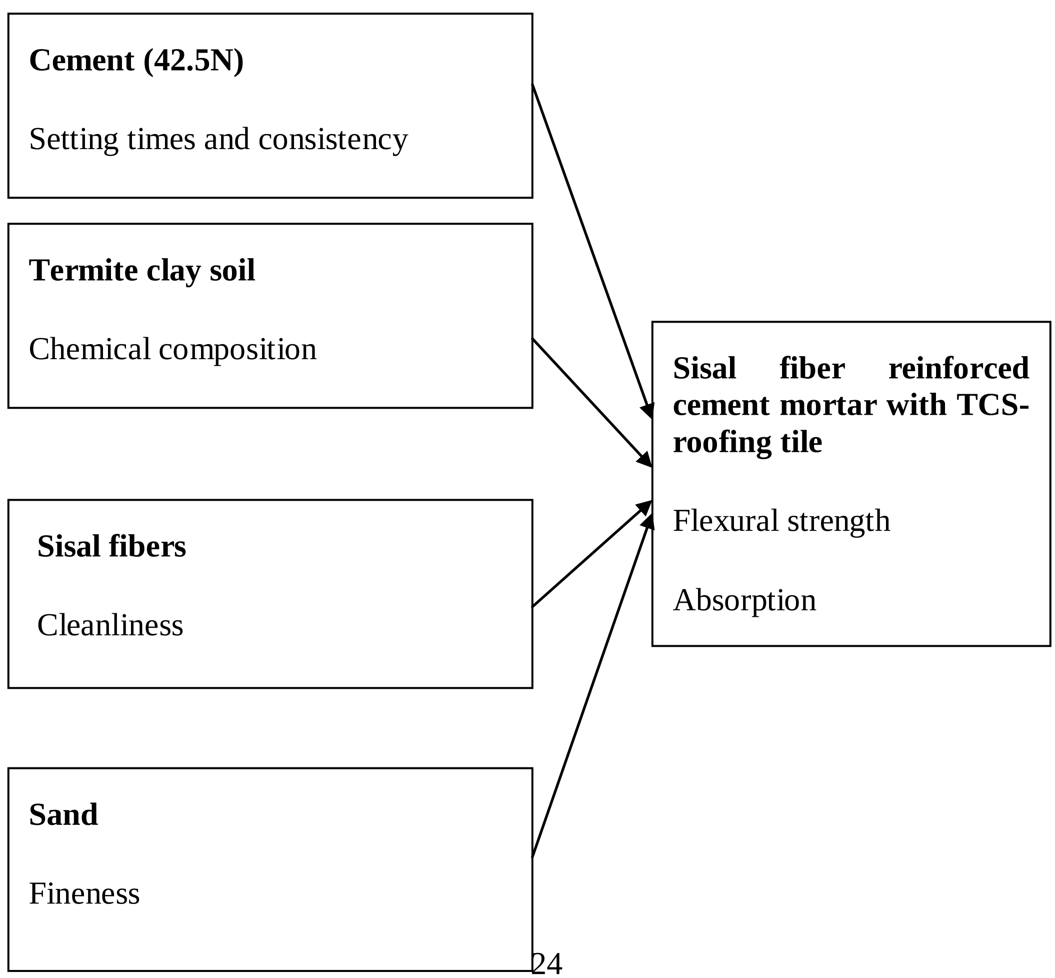
Fiber reinforced cement composites provides combined properties of interest to civil engineering applications which include strength, toughness, energy absorption, durability, corrosion resistance, water tightness, appearance and constructability. The role of fibers in cement mortar is not only to overcome the traditional weakness of inorganic cements namely, poor tensile strength and brittleness but also to improve the resistance to impact blast, explosion and other forms of dynamic loads (Sakthivel *et al.*, 2012). Sisal fiber is one of the prospective reinforcing materials that its use has been more empirical than technical until now. These fibers have always been considered promising as reinforcement of cement based matrices because of their availability, low cost and low consumption of energy (Yogesh, 2013). Sisal fiber is mainly used in the manufacture of ropes, textile materials and nets (Export processing zones authority, 2005). The main concern with natural fibers is one of long term strength and stability. Marked embrittlement of sisal fibers is caused by high alkalinity of the cement system (Brandt, 2009).

High energy consumption by cement industry causes environmental damage due to the high quantities of greenhouse gases released. Several researches are directed towards partial or full substitution of Portland cement. ASTM has set a minimum value of 70% sum of silica, alumina and iron oxides of the total compounds, with sulphur oxide less than 4% and loss of ignition less than 10% (Wafa *et al.*, 2012).

Extensive literature review has shown the importance of fiber reinforcement and in this case, sisal fiber. This includes strength, toughness, energy absorption, durability, corrosion resistance, water tightness, appearance and constructability. It has discussed embrittlement of sisal fiber in high alkaline environment such as cement media; in all these cases no research to the knowledge of the researcher has been done on the use of termite clay soil (ant hill soil) as a solution to deterioration of sisal fiber in cement matrix. No previous research to the knowledge of the researcher has studied the pH of termite clay soil with an aim to establishing if it can act as a solution to deterioration of sisal fibers in the cement matrix. This research has also studied chemical characteristics of inactivated termite clay soil, which has not been established in previous researches. Most research has dwelt on activated clay soil as pozzolanic materials. Therefore, the above advancement establishes the gap in this study.

### 2.7.1 Conceptual framework

Figure 2.1 below shows the conceptual framework of the research.



**Independent variables** **Dependent variables**

**Figure 2.1: Conceptual framework**

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Determining properties and optimal mix of termite clay soil

Termite clay soil for this research was obtained from Nduru Village, Majengo sub location in Siaya County. Cement (42.5N) was obtained from Thika Town. Sand was obtained from Kenya Bureau of Standards, the materials were sampled randomly; random sampling is a method of selecting a sample from a statistical population in such a way that every sample that could be selected has a predetermined probability of being selected.

### 3.1.1 Experimental setup

Termite clay soil was dried in the sun to reduce the moisture content; the soil was then ground to the desired fineness using a mechanical grinder at Jomo Kenyatta University of Agriculture and Technology (JKUAT). Sieve analysis was carried out and materials passing sieve 300µm was used in this research. With the use of mechanical manual grinder, obtaining samples less than 300µm was not possible. Studies undertaken by (James *et al.,* 2014) on chemically and mechanically activated clay pozzolana, the samples were crushed with a hammer mill to an average particle size of 80% passing a 100µm. But this research could not achieve the mentioned size with a mechanical grinder. Chemical characteristics of the soil was determined using Energy dispersive X ray diffraction(EDXRD), this is an analytical technique for characterizing materials, the pH of the soil was determined using the pH meter. The chemical and pH tests were carried out at the Ministry of Transport and Infrastructure, Materials Research Department located in Industrial Area Nairobi-Kenya. The following replacement levels of termite clay soil of 0, 10, 20, 30 and 40% for cement was used to determine the initial and final setting times, compressive strength, flexural strength and water absorption. The European Standard BS EN 196-1:2005 prescribes a compressive strength test on mortar specimens. The specimens are tested as 40mm equivalent cubes; they are derived from 40 by 40 by 160mm prisms, which are tested in flexure so as to break into halves and then the broken samples are tested in compression. This procedure was adopted in preparing and testing samples for compressive strength and flexural strength. The mortar was mixed on a cake mixer, using cement sand ratio of 1:3, and compacted on a jolting table with a drop of 15mm. The specimens were demoulded after 24 hours and thereafter cured in water at $20^0$C. For water absorption at 28 days period, the samples were removed from water, saturated weight measured, and then dried in an oven for 24 hours and dry weight measured in accordance to BS EN 196-1:2005.

### 3.1.2 Data collection procedure and analysis

The data required was obtained through laboratory experiments, the variables measured are compressive strength, flexural strength and water absorption. The laboratory experimental approach was used in this research. The data was analyzed using graphs and tables.

#### 3.1.2.1 Compressive strength

The analysis of data collected was done in the following manner; the results from the compression test were in the form of maximum load the cube can carry before it ultimately fails. The compressive stress was obtained by dividing the maximum load by the area normal to it.

$$б = P/A, \text{ (BS EN 196-1:2005)} \qquad \textbf{(3.1)}$$

Where;

P is the maximum load carried by the cube at failure.

A is the area normal to the load

$\sigma$ is the maximum compressive stress ($N/mm^2$)

### 3.1.2.2 Flexural strength

The result from the flexural strength test was presented in the form of the maximum load due to which a beam fails under bending compression. Using the fundamental equation of bending, the bending stresses were determined as shown in equation (3.2) below;

$$Fr = \frac{PL}{bd^2} \quad \text{(BS EN 196-1:2005)} \quad \textbf{(3.2)}$$

Where;

Fr is the flexural strength ($N/mm^2$)

P is the maximum applied load (N)

L is the average width of specimen (mm)

b is the average width of specimen (mm)

d is the Average depth of specimen (mm)

### 3.1.2.3 Water absorption

The test procedure involves drying the specimen to a constant weight, weighing it, immersing in water for a specified amount of time and weighing again. The increase in weight as a percentage of the original weight is expressed as its absorption as shown in equation (3.3) below;

$\{(W_s-W_d) \times 100\}/ W_s$, (BS EN 196-1:2005) **(3.3)**

Where;

$W_s$ is the saturated weight

$W_d$ is the dry weight

## 3.2 Determining the properties and optimal mix of sisal fiber reinforced cement mortar with termite clay soil

Sisal fiber used in this research was obtained from Juja Farm. Other materials required for casting specimens for sisal fiber reinforcement included sand and termite clay soil.

### 3.2.1 Experimental setup

Fixing the optimal termite clay soil replacement constant, sisal fiber reinforcement of 0, 0.5, 1.0, 1.5 and 2.0% was used to determine the properties of the composite which includes compressive strength, flexural strength, and water absorption and impact energy. Tests for compressive strength, flexural strength and absorption were done as outlined in (3.1.1) above.

For conducting the impact tests, a total of 15 cementitious specimens of sizes 140 by 140 by 10mm. Out of these three were control specimens (Cast with plain cement with optimal termite clay soil replacement without fibers) and twelve were tests specimens (Cast with blended cement using sisal fiber reinforcement of 0.5, 1.0, 1.5 and 2.0% by weight of cement and 10% TCS). The mortar was prepared with cement-sand ratio of 1:2, for fibrous cementitious mortar, the ultimate aim was to prepare the fibrous cementitious without clustering of fiber at one location in cement mortar. The impact energy was determined using a drop weight of steel mass of 1kg and the mass dropped on the tiles in the center from a predetermined height of 600mm. There was no standard in carrying out the impact test, but the procedure adopted by (Sakthivel *et al.*, 2012) was used in this research.

### 3.2.2 Data collection procedure and analysis

The data required was obtained through laboratory experiments; the variables measured are compressive strength, flexural strength, water absorption and impact energy. The laboratory experimental approach was used in this research. The data was analyzed using graphs and tables.

#### 3.2.2.1 Impact energy

The total energy absorbed by the cementitious composite slabs when struck by steel mass depends on the local energy absorbed both in contact zone and by the steel mass (impactor).The energy absorption was calculated from equation 3.4 below;

E= n x (wxh) Joules, (Sakthivel *et al.*, 2012) **(3.4)**

Where;

E is the energy (absorbed by the specimen on impact) in Joules,

n is the number of blows (on impact specimen),

w is the weight (of steel mass) in Newton,

h is the height (from where steel mass is dropped on the specimen) in meter.

In equation (1), constant values are w=9.81 N (weight of the ball) and h=0.6 m (height of fall), but the number of blows are based on the initial and final cracks.

The data was presented in form of tables and graphs.

#### 3.2.2.2 Residual Impact Strength Ratio (Irs)

Residual impact strength ratio is the ratio of energy absorbed at ultimate failure to energy absorbed at initial crack. This was calculated as shown in equation (3.5) below;

$I_{rs}$ = $\frac{\text{Energy absorbed up to ultimate failure}}{\text{Energy absorbed at first crack}}$, (Ramakrishna *et al*, 2011) **(3.5)**

### 3.3 Cost-benefit analysis of sisal fiber reinforced cement mortar with termite clay soil

#### 3.3.1 Cost analysis

The tile used in this research was 140 by 140 by 10mm. The procedure used in determining the cost of the roofing tiles was as follows: determining the weight of cement; determining the weight of sand; determining the weight of termite clay soil; determining the weight of sisal fibers; determining the formwork, labor, transport and other running costs.

These steps were outlined as shown below:

Volume of mortar = (0.14 x0.14x 0.01) = 0.000194$m^3$

Weight of mortar = (0.000194x2162) = 0.42Kg

Total proportion = (1 + 2 = 3)

Weight of cement= (0.42/3) x1 x 0.9 = 0.126 Kg (blended cement 0.9cement & 0.1TCS)

Weight of sand = (0.42/3) x2 = 0.28 Kg

Weight of TCS = (10% of 0.126 Kg) = 0.0126 Kg

Weight of fiber (assuming 2%) = (2%x 0.42Kg) =0.0084 Kg

The present cost for a kilogram of the components of the tile was as follows: cement (42.5N) was Ksh 19; sand was Ksh 0.75, TCS was Ksh 0.75 and fiber was Ksh 50. The following cost was assumed as follows: formwork was 25%; labor cost was 15%;

transport was 5%; other running cost was 10%. Therefore the cost of 0.14 by 0.14 $m^2$ was found to be Ksh 4.71 and therefore the cost of one square meter of tile was Ksh 240.

### 3.3.2 Benefits

The benefits expected to be derived from this research include the following: reduction of alkalinity of the cement media and therefore preservation of sisal fibers in the matrix; reduction in the emission of greenhouse gases by partial replacement of cement with the pozzolanic material; low energy consumption by using uncalcined termite clay soil; random mixer of fibers requires less mechanization and therefore reduction in the number of skilled personnel and low cost of the tile.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Properties and optimal mix of termite clay soil

The section deals the properties of TCS which include: chemical composition; pH; compressive strength; flexural strength and absorption. It also provides the optimal replacement of TCS for cement.

### 4.1.1 Chemical composition of termite clay soil and pH

Table 4.1 below shows the results of the chemical analysis of termite clay soil. Table 4.1 below shows the results of the chemical analysis of termite clay soil. The table shows the chemical composition of TCS in percentages. This analysis is important because it affirms the pozzolanic character of the soil.

**Table 4.1: Chemical composition of termite clay soil**

| Chemical composition | Quantities (%) |
| --- | --- |
| $SiO_2$ | 59.096 |
| $Fe_2O_3$ | 18.417 |
| $Al_2O_3$ | 15.540 |
| $TiO_2$ | 2.266 |
| $K_2O$ | 2.258 |
| $SO_3$ | 0.744 |
| CaO | 0.716 |
| MnO | 0.646 |
| $ZrO_2$ | 0.202 |
| $V_2O_5$ | 0.088 |
| NbO | 0.027 |

Table 4.2 below shows the pH of termite clay soil samples. Different samples were taken to determine the pH of the soil. This is important because the cement media is alkaline and the research uses sisal fiber as reinforcement in cement mortar. Since sisal fiber de-composes in an alkaline media, it is important to determine whether the soil is acidic.

Table 4.2: pH of termite clay soil samples

| TCS Samples | pH value |
| --- | --- |

| | |
|---|---|
| **TCS1** | 4.92 |
| **TCS2** | 5.49 |
| **TCS3** | 5.32 |
| **TCS4** | 5.11 |
| **Average pH** | 5.21 |

Chemical analysis of TCS was carried out using Energy dispersive X ray diffraction (EDXRD); this is an analytical technique for characterizing materials. As shown in Table 4.1, the main components of TCS are $SiO_2$ (59.1%), $Fe_2O_3$ (18.4%), $Al_2O_3$ (15.5%). The $SiO_2$ content of the soil exceeded the minimum limit of 25% as prescribed by EN 197-1 for pozzolana samples. The sum of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ also exceeded the minimum limit of 70% and $SO_3$ (0.7%) was less than the maximum limit of 4% prescribed by ASTM C 618 for the pozzolana samples. Therefore the material was found to be chemically suitable as a pozzolanic material. The sum of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ equals to 93.053%, which shows that the material is highly pozzolanic and therefore can be used as a pozzolana to partially replace cement. A relatively high content of active phases ($SiO_2$ +$Al_2O_3$) with (74.6%) indicates the acidic character of TCS. The pH was also determined by pH meter, giving an average value of 5.21, which shows that the material was acidic and therefore could reduce the high alkalinity of the cement matrix thus reducing embrittlement of the sisal fibers in the matrix. The reactive silica was determined to be 59.1% indicating the pozzolanic character of TCS and therefore its suitability for use as a pozzolana.

### 4.1.2 Setting times of termite clay soil partial replacement for cement

Figure 4.1 below shows the results of setting times for termite clay soil partial replacement in cement.

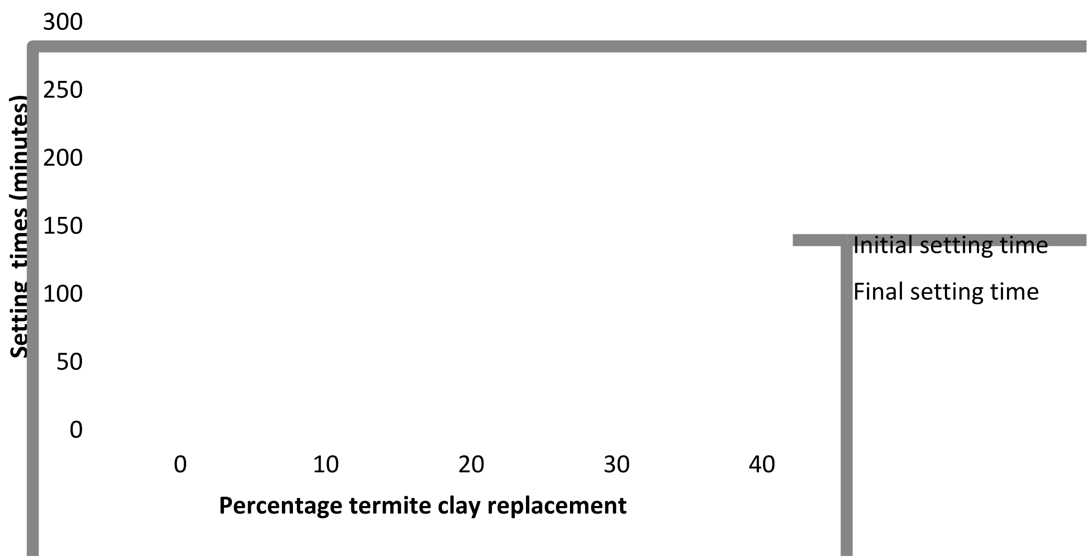



**Figure 4.1: Setting times against percentage of termite clay replacement**

Figure 4.1 shows the initial and final setting times of TCS partial replacement for cement. The initial and final setting times increased with increase in termite clay soil replacement for cement. The results for initial setting time for all the replacements meet the requirement of KS EAS 18-1:2001 for 42.5N Cement of ≥60 minutes as shown in Appendix 1. The increase in setting times could be attributed to the increase in consistency as shown in Appendix 1. The pozzolanic reaction is much slower than normal hydration reaction even into months and years if water is available. For tiles, the longer hydration process does not pose a great problem in construction because tiles are used later in the construction process.

### 4.1.3 Compressive strength of termite clay soil partial replacement for cement

Figure 4.2 below shows the results for compressive strength for termite clay soil partial replacement for cement at 2 days.

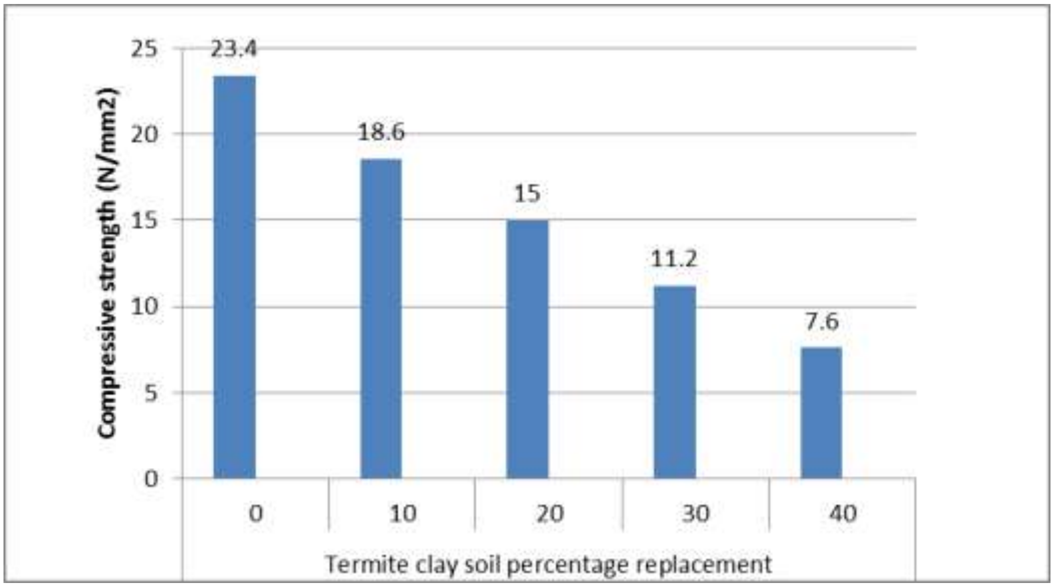



**Figure 4.2: Compressive strength at 2days against percentage TCS replacement**

Figure 4.3 below shows compressive strength of termite clay soil partial replacement for cement at 28 days.

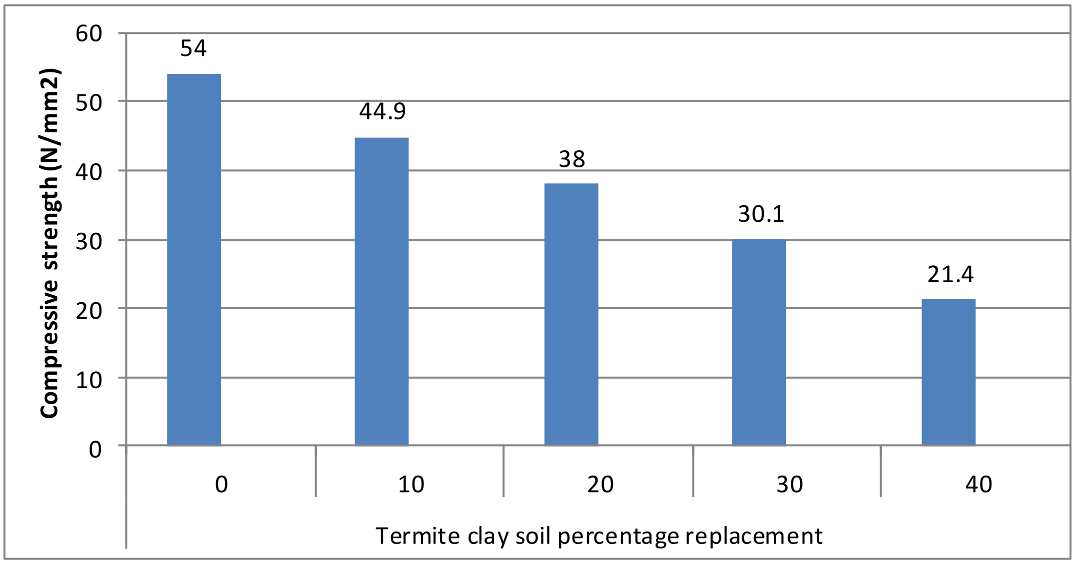



**Figure 4.3: Compressive strength against percentage TCS replacement for cement at 28 days.**

Figure 4.2 and 4.3, shows the compressive strength of termite clay soil partial replacement for cement at percentage replacement of 0, 10, 20, 30 and 40% mortar cubes at 2 days and 28 days. The compressive strength decreased with increase in percentage replacements of TCS for cement. At 2days strength, up to 30% TCS replacement satisfied the requirement of KS EAS 18-1:2001 of minimum of 10N/mm$^2$ for 42.5N Cement as shown in Figure 4.2 and Appendix 2. At 28 days strength, up to 10% TCS replacement satisfied the requirement of KS EAS 18-1:2001 of minimum of 42.5 N/mm$^2$ for 42.5N Cement as shown in Appendix 2.From Figure 4.2 TCS 40% has strength of 32.5% of the control at 2 day strength. Figure 4.3 TCS 40% has strength of 39.6% of the control at 28 days strength. This shows that with time TCS 40% is catching up with TCS 0% in terms of strength. It should be noted that reduction in compressive strength with increase in TCS% partial replacement, could be attributed to the slow development of pozzolanic reaction and an assumption can be made that, measurements at 90 days could probably show high strength. Studies done by (Ravikumar *et al.,* 2013), indicates that there is gradual decrease of compressive from 0 to 60 days and thereafter an increase in compressive strength. This research also showed a gradual decrease up to 28 days. This therefore indicates that test up to 90 days could yield higher results.

### 4.1.4 Flexural strength of termite clay soil partial replacement for cement

Figure 4.4 below shows the results for flexural strength of termite clay soil partial replacement for cement at 2 days.

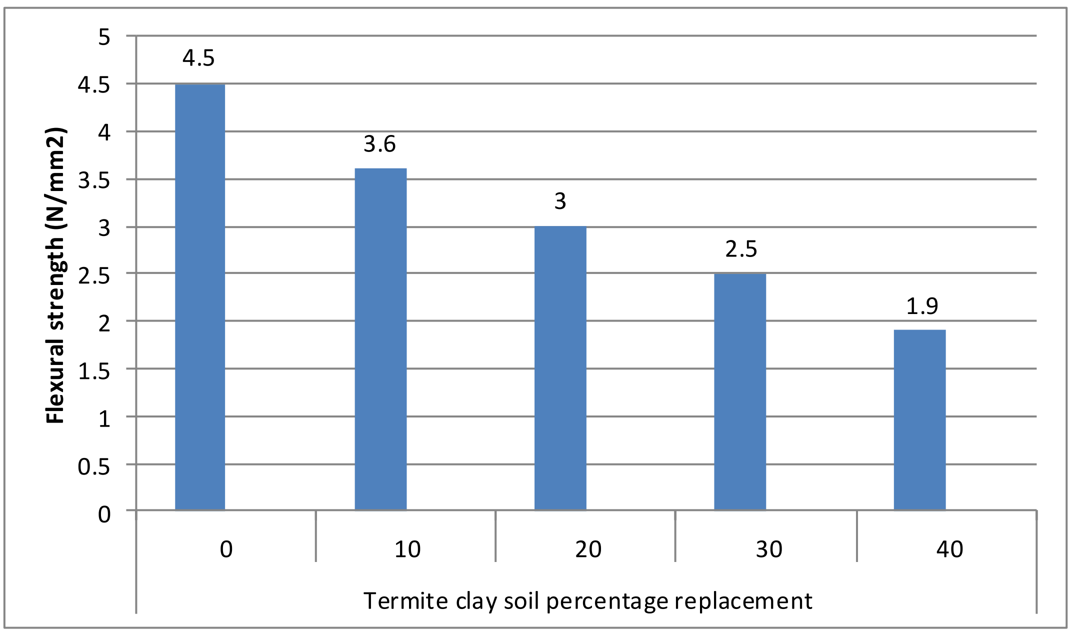



**Figure 4.4: Flexural strength against percentage TCS replacement for cement at 2 days**

Figure 4.5 below shows the results of flexural strength of termite clay soil partial replacement for cement at 28 days.

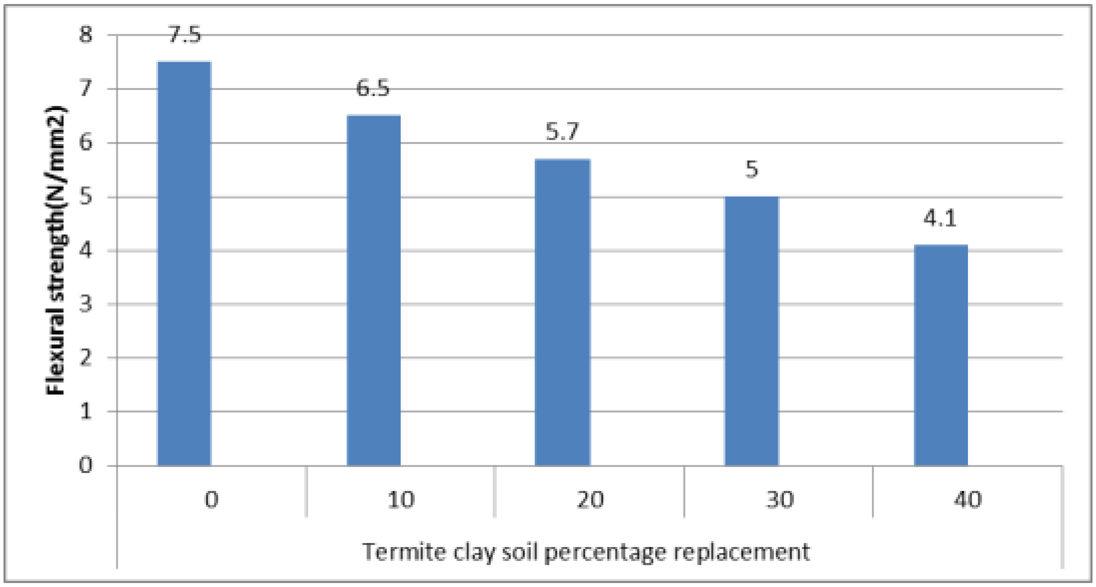



**Figure 4.5: Flexural strength against percentage TCS replacement for cement at 28 days.**

Figure 4.4 and 4.5, shows the flexural strength of TCS partial replacement for cement at percentages of 0, 10, 20, 30 and 40% mortar prisms at 2 days and 28 days. The flexural strength decreased with increase in percentage replacements. At 2 days strength, up to 20% replacement satisfied the requirement of KS 02-444: 1984 Specification for concrete roofing tiles of minimum 2.80 N/mm$^2$ for individual tiles as shown in Appendix 3. At 28 days strength, up to 40% replacement satisfied the requirement of KS 02-444: 1984 Specification for concrete roofing tiles of minimum 2.80 N/mm$^2$ for individual tiles as shown in Appendix 3. From Figure 4.4, TCS 40 % has strength of 42% of the control at 2 day strength and in Figure 4.5; TCS 40% has strength of 55% of the control at 28 day strength. This shows that with time TCS 40% is catching up with TCS 0% in terms of strength. The result affirms the existing knowledge of low early strength which is a setback in the use of pozzolanas and it should be noted that measurements at 90 days could yield high strengths. Research on pozzolanic materials by (Ravikumar *et al.*, 2013), showed that there is an increase in flexural strength from 60 days with replacement of cement with pozzolanic materials. This finding agrees with the statement in this study that affirms that tests at 90 days could yield results.

### 4.1.5 Absorption rate of termite clay soil partial replacement for cement

Figure 4.6 below shows the results of absorption of termite clay soil partial replacement for cement at 28 days.

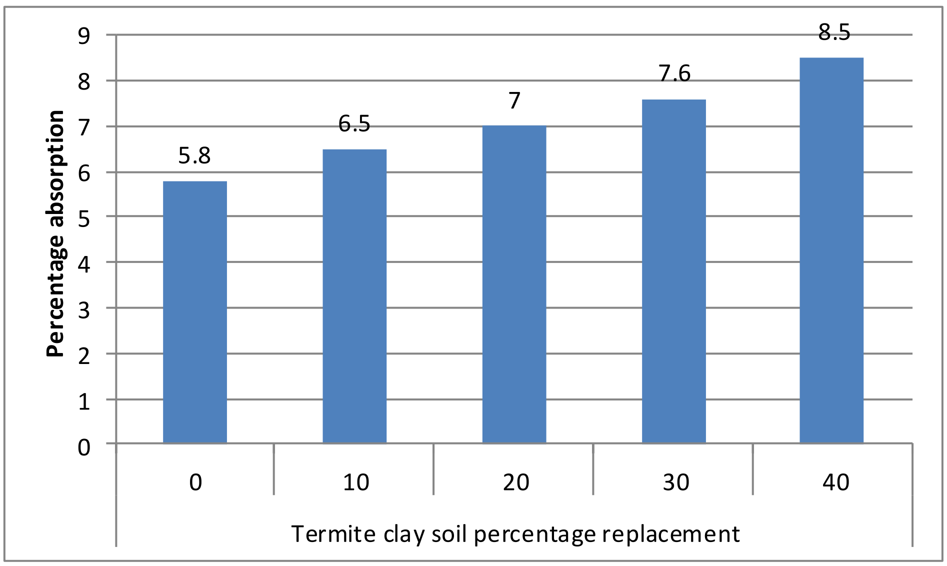



**Figure 4.6: Absorption against percentage TCS replacement for cement at 28 days**

Figure 4.6, shows absorption rates of TCS partial replacement for cement at percentages of 0, 10, 20, 30 and 40%. The absorption rate increased with increase in percentage replacement. Up to 40 % replacement satisfied the requirement of KS 02-444: 1984 Specification for concrete roofing tiles of maximum 10 % water absorption as shown in Appendix 4. The absorption of TCS mortars was found to increase due to more voids and pores; it absorbed more water which can be observed from the normal consistency (Rezaul et al., 2014) as shown in Appendix 1. Studies done by (Sadrmomtaz *et al.*, 2009), showed an increase in water absorption with increase in pozzolanic replacement, which agrees with this findings. The absorption rate for higher TCS content mixes probably would increase with age with measurements at 90 days.

### 4.1.6 Optimum replacement of percentage termite clay soil replacement

Figure 4.7 below shows the results of flexural strength and absorption for termite clay soil partial replacement for cement at 28 days. The two are plotted together to determine the optimality of TCS replacement.

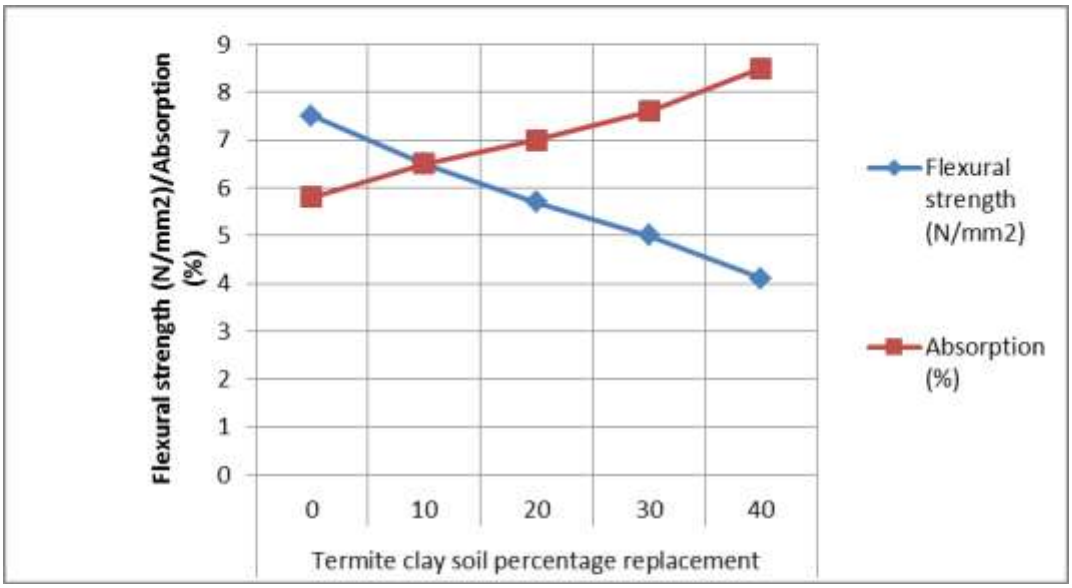



**Figure 4.7: Flexural strength and absorption against percentage TCS partial replacement**

The optimum replacement of TCS in cement was determined by drawing a graph of absorption rate and flexural strength at 28 days against the TCS percentage replacement. Since the key parameters in testing roofing tile are absorption and flexural strength, the intersection of the two lines was determined to be the optimal point. This was found to be 10% TCS which also satisfied the requirement of compressive strength in KS EAS 18-1: 2001 of ≥ 42.5N/mm$^2$ and ≤62.5N/mm$^2$ for 42.5N cement. At TCS 10% partial replacement, the flexural strength was found to be 6.5N/mm$^2$ which satisfied the requirement of KS 02-444:1984 Specification for concrete roofing tiles of minimum 2.80 N/mm$^2$ for individual tiles. The absorption rate was found to be 6.5% which satisfied KS 02-444:1984 Specification for concrete roofing tiles of maximum 10%.

## 4.2 Properties and optimal mix of sisal fiber reinforced cement mortar with termite clay soil

The properties of sisal fiber reinforced cement mortar with TCS determined in this section include: compressive strength; flexural strength, absorption and impact strength.

### 4.2.1 Flexural strength and Compressive strength of Sisal fiber reinforcement in cement.

Figure 4.8 below shows the results of flexural strength of sisal fiber reinforced cement with termite clay soil partial replacement for cement at 28 days. Figure 4.9 below shows the results of the compressive strength of sisal fiber reinforced cement mortar with termite clay soil partial replacement for cement at 28 days.

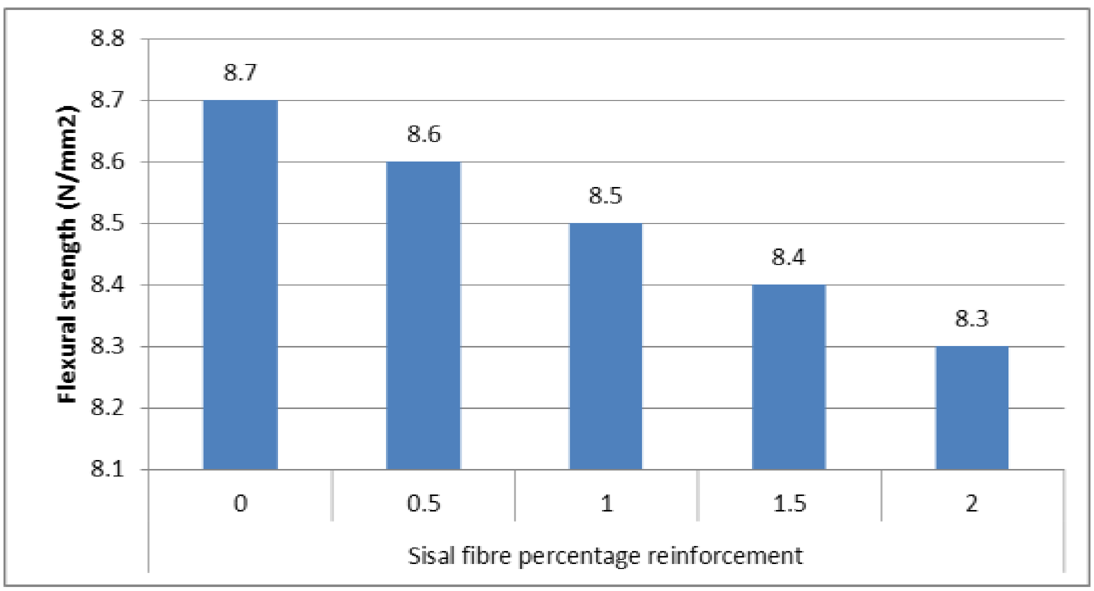



**Figure 4.8: Flexural strength against percentage SF reinforcement at 28 days**

Figure 4.8 shows the flexural strength of sisal fiber reinforced cement mortar at percentages of 0, 0.5, 1.0, 1.5 and 2.0%. The flexural strength decreased with increased sisal fiber reinforcement as shown in Appendix 4. Up to 2.0% reinforcement satisfied KS 02-444: 1984 Specification for concrete roofing tiles of minimum 2.80 N/mm$^2$ for individual tiles. The consistent reduction in flexural strength could be attributed to improper mixing of fibers with matrix as a result of balling of fibers, increased vibration to reduce air voids from the mix causes problem of bleeding and thus decreases the flexural strength. Studies carried out by (Olonade *et al.,* 2013) showed that flexural strength of coconut fibers reinforced concrete increases with increase in fiber reinforcement. But this particular research involved also a partial replacement with a pozzolanic material which justifies the decrease in strength up to 28 days. Sayyed *et al.*, (2012) observed local aggregation (clumping) and folding of fibers (balling) as two problems with fiber soil composites. Similar observation is attributed to this research.

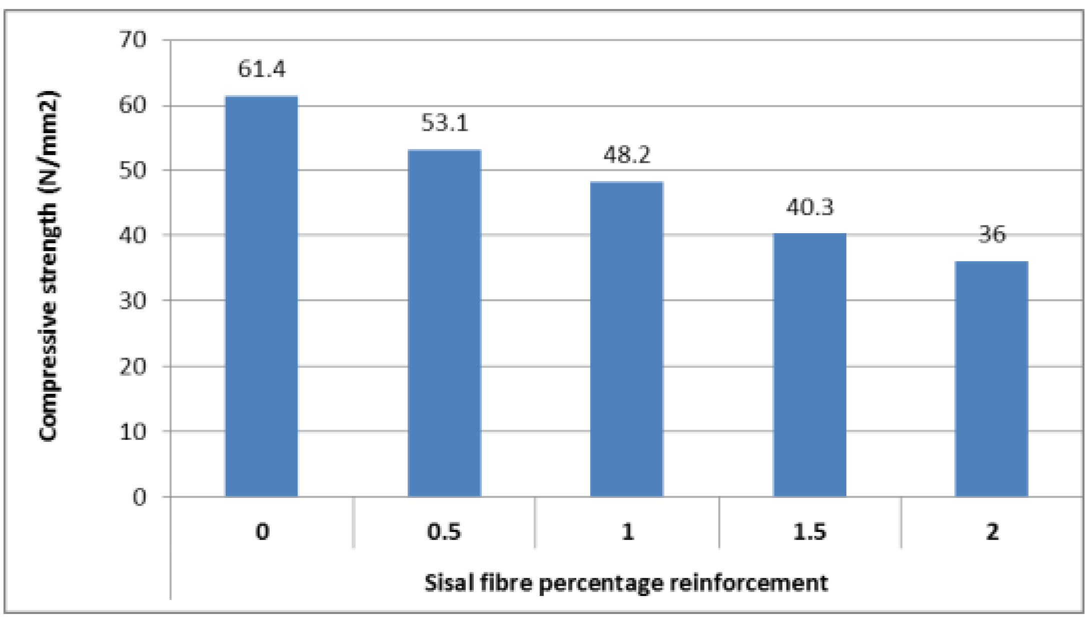



**Figure 4.9: Compressive strength of percentage SF reinforcement at 28 days**

Figure 4.9, shows Compressive strength of sisal fiber reinforced cement mortar with SF reinforcement at percentages of 0, 0.5, 1.0, 1.5 and 2.0%. Compressive strength decreased with increased sisal fiber reinforcement as shown in Appendix 4. The decrease in compressive strength could be due to porosity of the composite material as a result of fiber addition. However, the SF 0% mortar specimens loaded in compression suffered a highly unstable mode of failure, whereas the fiber reinforced mortars showed a more stable behavior, characterized by larger deformations with a gradual drop in the applied loads (Robert *et al.*, 2013). It should be noted that compressive strength is not used as a parameter in testing concrete roofing tiles. Olonade *et al.*, (2013), observed that there is an increase in compressive strength with increase in coconut fiber reinforcement in concrete. This research involved the use of termite clay soil with pozzolanic properties which justifies the reduction in compressive strength up to 28 days.

### 4.2.2 Absorption rate of Sisal fiber reinforcement in cement with termite clay soil

Figure 4.10 below shows the results of absorption for sisal fiber reinforced cement mortar with termite clay soil partial replacement for cement at 28 days.

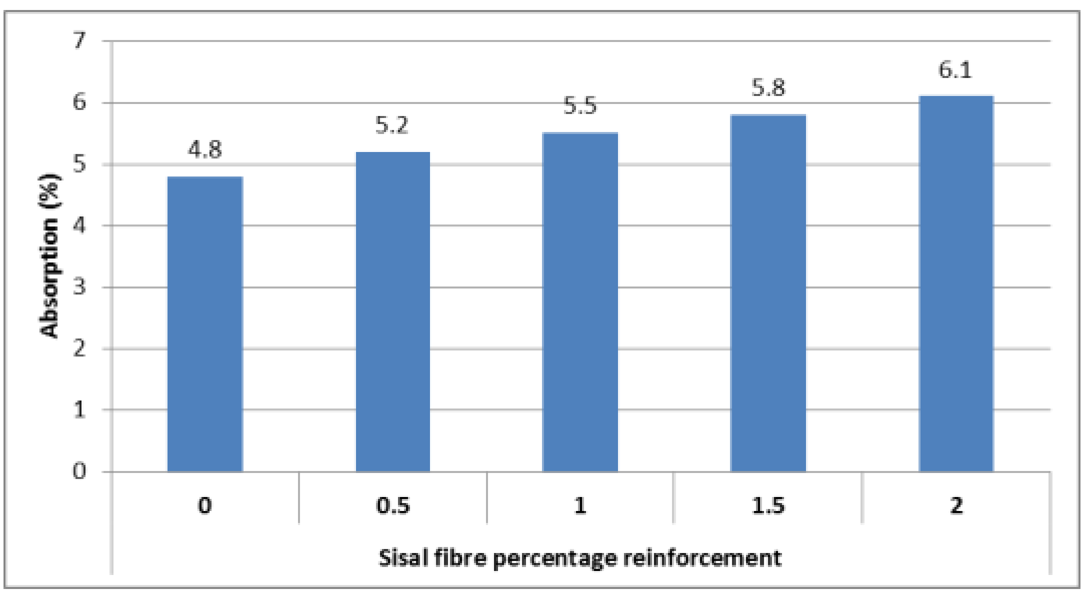



**Figure 4.20: Absorption against percentage SF reinforcement in cement mortar at 28 days.**

Figure 4.10, shows Absorption rate of sisal fiber reinforced cement mortar with SF reinforcement for cement at percentages of 0, 0.5, 1.0, 1.5 and 2.0%. The absorption rate increased with increased percentage reinforcement. Up to SF 2.0% reinforcement satisfied the requirement of KS 02-444: 1984 Specification for concrete roofing tiles for maximum absorption of 10% as shown in Appendix 6. The increase in absorption with increase in sisal fiber reinforcement could be due to more voids and pores created in the matrix because the mixing was done manually (when sisal fibers were added, the cake mixer could not mix the samples). It was found that the mortar mixer could not work effectively in mixing samples with sisal fibers. The manual mixing thus created more spaces leading to rise in absorption.  Studies done by Omoniyi *et al.*, (2015), on Kenaf fibers showed an increase in water absorption with increase in fiber reinforcement.

### 4.2.3 Impact energy of sisal fiber reinforcement for cement mortar

Figure 4.11 below shows the residual impact strength ratio of sisal fiber reinforced cement mortar with termite clay soil partial replacement for cement at 28 days.

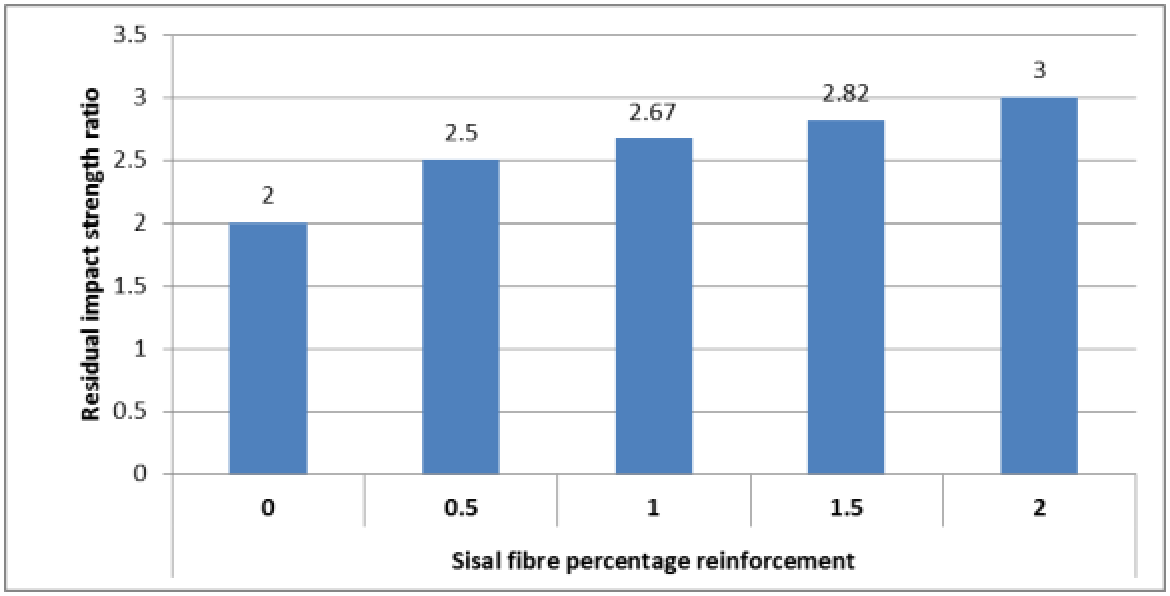



**Figure 4.31: Residual impact strength ratio against percentage SF reinforcement**

Figure 4.11, shows Residual impact strength ratio ($I_{rs}$) of sisal fiber reinforced cement mortar with SSF reinforcement for cement at reinforcement percentages of 0, 0.5, 1.0, 1.5 and 2.0%. $I_{rs}$ increased with increase in SSF percentage reinforcement. Both energy at first crack and ultimate failure increased with increase in reinforcement as shown in Appendix 7. At 2% sisal fiber reinforcement was 3.00. Residual impact strength ratio is closely related to the coefficient of restitution (CoR). CoR is defined as a magnitude that provides information on the quantity of energy lost in the elastic shock between steel and the fair face of a ceramic tile (ISO 10545-5:1996). BS EN 14411:2012 recommends a minimum value of 0.55 CoR for tiles intended for floors with low mechanical requirements. Therefore, up to SF 2.0% was found to be 3.00 which satisfied the requirement of BS EN 14411: 2012. The findings concurs with the studies done by (Sakthivel *et al.*, 2013), which recorded an increase in energy absorption capacity of cementitious slabs reinforced with stainless steel fibers. It should be noted that, there is no available standard known to the researcher which specifies the impact energy or CoR for roofing tiles. Hence the adoption of the requirements of BS EN 14411: 2012 for floor tiles.

## 4.3 Cost-benefit analysis of sisal fiber reinforced cement mortar with termite clay soil

Table 4.3 below shows the cost analysis of sisal fiber reinforced tile with termite clay soil partial replacement. The cost given is based on tile of size 140 by 140 by 10mm and 1000 by 1000 by 10mm. It is assumed that the materials are locally available and therefore the transport cost was assumed to be 5%. The cost of formwork was assumed to be 25% and labor was 15%.

**Table 4.3: Cost analysis**

| Contents | Weight (Kg) | Unit rate (Ksh) per Kg | Amount (Ksh) |
|---|---|---|---|
| Cement | 0.126Kgs | 19 | 2.40 |
| Sand | 0.28Kgs | 0.75 | 0.21 |
| TCS | 0.0126 Kgs | 0.75 | 0.01 |
| Fiber | 0.0084 Kgs | 50 | 0.42 |
| Subtotal 1 | | | 3.04 |
| Formwork cost 25% | | | 0.76 |
| Labor cost of 15% | | | 0.46 |
| Transport cost 5% | | | 0.15 |
| Other running costs 10% | | | 0.30 |
| Total cost of 0.14 by 0.14 $m^2$ | | | Ksh 4.71 |
| Total cost of 1$m^2$ | | | Ksh 240 |

From Table 4.3, the cost per tile of 140 by 140 by 10 mm was Ksh 4.71 and the cost per square meter of this tile was Ksh 240. This indicates that this tile is cheaper as compared to other tiles as shown in Table 4.4 below;

**Table 4.4: Cost of other roofing materials per square meter**

| Type of roofing materials | Cost per square meter in Ksh |
|---|---|
| Proposed tile(Sisal fiber reinforced cement mortar with TCS) | 240 |
| Corrugated iron sheets | 300 |
| Pre-painted sheets | 700 |
| Clay roofing tiles | 800 |
| Slate stone tiles | 1500 |
| Wooden tiles | 1800 |
| Stone coated steel tiles | 2000 |

Roofing tiles and materials are sold per square meter. From the above table, the proposed tile is cheaper. From Figure 4.11, the Residual impact strength ratio was very high giving a value of 3.00 for SF 2.0%, and this showed that the tile is strong. In addition to low cost of tiles made from sisal fiber reinforced cement mortar with termite clay soil partial replacement, the following benefits accrue from its use: reduction of alkalinity of the cement media and therefore preservation of sisal fibers in the matrix; reduction in the emission of greenhouse gases by partial replacement of cement with the pozzolanic material; low energy consumption by using uncalcined termite clay soil; random mixer of fibers requires less mechanization and therefore reduction in the number of skilled personnel. These benefits could not be expressed in monetary terms because it was not within the scope of this research.

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

### 5.1.1 Properties and optimal mix of termite clay soil

i. The properties of termite clay soil include the fact that the material is pozzolanic with the sum of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ constituting 93% of the material, leading to the conclusion that it satisfied the requirement of ASTM C618 of minimum of 70%.

ii. The pH of termite clay soil was 5.21 which showed that the soil was acidic leading to the conclusion that, it is suitable for reducing the alkalinity of the cement matrix, consequently preserving the sisal fibers.

iii. The optimal replacement for uncalcined termite clay soil (TCS) was 10% with flexural strength of 6.5N/mm$^2$ and water absorption of 6.5%, leading to a conclusion that it satisfied the requirement of KS 02-444: 1984, of minimum flexural strength of 2.80N/mm$^2$ and maximum water absorption of 10%.

### 5.1.2 Properties and optimal mix of sisal fiber reinforced cement mortar with termite clay soil

i. The optimal reinforcement of sisal fiber was 2.0%, with water absorption of 6.1% and flexural strength of 8.3N/mm$^2$ at 28 days which satisfied the requirement of KS 02-444: 1984, of 10% for water absorption and a minimum of 2.8 N/mm$^2$ for flexural strength for individual tiles.

ii. The residual impact strength ratio ($I_{rs}$) at optimal reinforcement was 3.00 which satisfied the requirement of BS EN 14411: 2012 of minimum 0.55 for tiles intended for floors with low mechanical requirements. It should be noted that, there is no available standard known to the researcher which specifies the impact energy or CoR for roofing tiles.

### 5.1.3 Cost-benefit of sisal fiber reinforced cement mortar with termite clay soil

i. Cost per square meter was Ksh 240, which is cheaper as compared to other roofing materials which are in the range of 300 to Ksh 2000. There are also associated benefits which include: reduction of alkalinity of the cement media and therefore preservation of sisal fibers in the matrix; reduction in the emission of greenhouse gases by partial replacement of cement with the pozzolanic material and low energy consumption.

## 5.2 Recommendations

### 5.2.1 Recommendations

i. It is recommended that 10% inactivated termite clay soil (TCS) be used as partial replacement for cement and that up to 2.0% sisal fiber reinforcement be used in concrete roofing tiles with TCS as partial replacement for cement, with a cement-sand ratio of 1:2 and water cement ratio of 0.5.

ii. The different samples of TCS showed different values of pH which is critical in manufacturing sisal fibers reinforced roofing tiles. It is recommended that before it is used, the chemical analysis and pH should be determined.

### 5.2.2 Recommended areas for further research

i. It is recommended that further studies be done on the use of calcined termite clay soil as partial replacement for cement with sisal fiber reinforcement for use in roofing tiles.

ii. It is recommended that further studies be done on the test on sisal fiber reinforced cement mortar with termite clay soil at ages beyond 28 days.

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## APPENDICES

Appendix 1: Setting times and consistencies of termite clay soil partial replacement in cement.

| Cement % | TCS % | Consistency % | Initial setting time(min) | Final setting time(min) |
|---|---|---|---|---|
| 100 | 0 | 25 | 110 | 195 |
| 90 | 10 | 27 | 124 | 199 |
| 80 | 20 | 28 | 134 | 209 |
| 70 | 30 | 33 | 145 | 220 |
| 60 | 40 | 34 | 154 | 240 |

Appendix 2: Compressive strength for termite clay soil partial replacement.

| C % | TCS (%) | W/C | 2D,(C.S) | 28 D (C.S) |
|---|---|---|---|---|
| 100 | 0 | 0.5 | 23.4 | 54.0 |

| | | | | |
|---|---|---|---|---|
| 90 | 10 | 0.5 | 18.6 | 43.6 |
| 80 | 20 | 0.5 | 15.0 | 38.0 |
| 70 | 30 | 0.5 | 11.2 | 30.1 |
| 60 | 40 | 0.5 | 7.6 | 21.4 |

Appendix 3: Flexural strength for termite clay soil partial replacement in cement.

| C% | TCS% | W/C | 2D (F.S) | 28 D (F.S) |
|---|---|---|---|---|
| 100 | 0 | 0.5 | 4.5 | 7.5 |
| 90 | 10 | 0.5 | 3.6 | 6.5 |
| 80 | 20 | 0.5 | 3.3 | 5.7 |
| 70 | 30 | 0.5 | 2.5 | 5.0 |
| 60 | 40 | 0.5 | 1.9 | 4.1 |

Appendix 4: Flexural and Compressive strength for sisal fiber reinforcement.

| % SFR by weight | F.S ($N/mm^2$) | C.S ($N/mm^2$) | ABS (%) |
|---|---|---|---|
| 0 | 8.7 | 61.4 | 4.8 |
| 0.5 | 8.6 | 52.9 | 5.2 |
| 1 | 8.5 | 49.2 | 5.5 |

| | | | |
|---|---|---|---|
| 1.5 | 8.3 | 40.3 | 5.8 |
| 2.0 | 8.2 | 37.0 | 6.1 |

Appendix 5: Absorption at 28 days for termite clay soil partial replacement.

| TCS (%) | S.W (g) | D.W(g) | ABS (%) |
|---|---|---|---|
| 0 | 611.8 | 576.3 | 5.8 |
| 10 | 602.4 | 563.2 | 6.5 |
| 20 | 591.0 | 549.3 | 7.0 |
| 30 | 614.4 | 567.6 | 7.6 |
| 40 | 620.4 | 567.7 | 8.5 |

Appendix 6: Absorption 28 days for sisal fiber reinforcement.

| SSF (%) | SW(g) | DW(g) | ABS (%) |
|---|---|---|---|
| 0 | 661.9 | 632.9 | 4.4 |
| 0.5 | 697.9 | 661.6 | 5.2 |
| 1.0 | 737.8 | 697.2 | 5.5 |
| 1.5 | 743.2 | 700.0 | 5.8 |
| 2.0 | 760.9 | 714.4 | 6.1 |

Appendix 7: Impact energy and Residual impact strength ratio for sisal fiber reinforced tiles.

| % SFR by | First Crack | Ultimate failure | Energy at 1st Crack | Energy at Ultimate crack(Joule | Residual Impact Strength |
|---|---|---|---|---|---|

| weight | (N) | (N) | (Joules)A | s)B | Ratio (B/A) |
|---|---|---|---|---|---|
| 0 | 10 | 20 | 58.86 | 117.72 | 2.00 |
| 0.5 | 12 | 30 | 70.63 | 176.58 | 2.50 |
| 1 | 15 | 40 | 88.29 | 235.44 | 2.67 |
| 1.5 | 17 | 48 | 100.06<br>2 | 282.52<br>8 | 2.82 |
| 2.0 | 20 | 60 | 117.72 | 353.16 | 3.00 |