MECHANICAL PROPERTIES OF SISAL FIBRE REINFORCED CONCRETE

BY

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This Thesis is submitted to the University of Nairobi in partial fulfilment for the Degree of Master of Science in Agricultural Engineering

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DECLARATION

I declare that this is my original work and has not been presented for a degree in any other University.

Date 8.2.1994

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This Thesis has been submitted with our approval as University supervisors:

Date 15/2/94

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Date 25/2/94

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DEDICATED TO MY PARENTS

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ABSTRACT

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Reinforcement of brittle matrices with fibres of different kinds has been shown to improve the mechanical properties of these materials.

In this study, mechanical properties of sisal fibre reinforced concrete were examined using the Tensile test, and the Four-point bending test.The Flexural strength, Tensile strength, Toughness and the Interfacial bond strength were examined.Two forms of reinforcements were examined under varying volume fractions. These were, parallel fibre reinforcement with uniaxial fibres aligned in the direction of the stress field, and chopped fibres randomly reinforced in the matrix.

Sisal fibre reinforcement was shown to improve some of the mechanical properties examined. The Flexural strength and the Tensile strength were seen to increase considerably with fibre volume fractions for parallel fibre reinforcement. No increase in Flexural and Tensile strengths was observed for the chopped fibres reinforcement. Toughness was observed to increase considerably with fibre volume fractions in all cases except for chopped fibres reinforced samples tested in tension. During failure, fibre pull-out was observed and the composites behaved in a ductile manner with the fibres being able to sustain some load even when cracks had developed fully across the specimen.

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NOTATION

Symbols where not otherwise identified will be as follows:

Subscripts c, f and m refer to composite, fibre and matrix respectively.

E	-	Modulus of Elasticity
G	-	Shear Modulus
σ	-	Normal Stress
τ	-	Shear Stress
ϵ	-	Normal Strain
γ	-	Shear Strain
C	-	Stiffness Matrix Component
S	-	Compliance Matrix Component
ν	-	Poisson's Ratio
V	-	Volume Fraction
β	-	Fibre Orientation Factor
N	-	Newton
Pa	-	Pascals
fn	-	function
FS	-	Flexural Strength
TS	-	Tensile Strength
TG	-	Toughness

1.0 INTRODUCTION

Several examples of fibre reinforcement exist in nature as well as in the history of humankind. Nature has provided composite materials in the form of Bamboo, Bones and Vegetables (Nicholls, 1976). Wood is a composite of cellulose fibres, strong in tension in the direction parallel to the grain but flexible, cemented together with lignin which provides stiffness. Bone is a composite of the strong but soft protein collagen and the hard but brittle mineral apatite (Nicholls, 1976). According to Aziz et al (1984), the use of straw in semi-dried mud-bricks and walls, and horse hair in mortar predates the use of conventional reinforced concretes.

For example, as cited by Jones (1975), the Israelites used straw to strengthen mud bricks and walls. The Egyptians used plywood after they realized that wood could be rearranged to achieve superior properties (Jones, 1975). Jones (1975), again, reports that medieval swords and armour were made with layers of different materials. Another form of reinforcement that has existed for a long time in some parts of the world is the wall structure of mud huts, which is supported by a framework of sticks.

Cement based materials in the form of mortars or concrete are attractive for use as constructional materials since they are cheap, durable and have adequate compressive strength and stiffness for structural use (Keer, 1984). Additionally in the fresh state they are readily moulded almost to any desired shape (Keer, 1984). Their deficiencies lie in their brittle characteristics, poor tensile and impact strengths and their susceptibility to moisture movements (Keer, 1984).

The concept of reinforcing cement matrices to overcome their brittle characteristics has made cement composite one of the best and mostly widely used construction material of the twentieth century. Steel has established itself as a leading reinforcing material for cement composites (Subrahmanyam, 1984). Unfortunately acute shortages of steel have been experienced in several parts of the world from time to time. Also in most of the developing countries, steel continues to be costly, scarce and often an imported item (Subrahmanyan, 1984). Asbestos fibre is another popular reinforcing material of cement sheets, pipes and boards (Keer, 1984, Aziz et al 1984, and Subrahmanyam, 1984). The health hazards associated with the use of asbestos fibres are now well known and asbestos fibres are expected to be withdrawn from use in the near future (Subrahmanyam, 1984).

On the other hand, particularly in the developing countries, the housing needs are increasing at very high rates due to increasing population and urbanization associated with industrial developments (Subrahmanyam, 1984). Therefore there is great need for effective low cost and alternative reinforcements for cement composites.

Natural fibre is one of the alternative materials with a very good potential for reinforcing cement matrices, especially in the developing nations (Persson and Skarendahl, 1980).

Natural fibres are available in most developing countries and require only a low degree of industrialization for their processing (Aziz et al., 1984). In comparison with an equivalent volume or weight of the most common synthetic fibres, Aziz et al (1984) reports that the energy required for their production is small and hence the cost of fabricating these composites is also low. The techniques for fabrication require a small number of trained personnel. The use of such fibres in concrete is therefore particularly attractive to the developing countries with their shortage of skilled manpower and capital, and their need for good quality locally-produced low-cost building materials.

One of the natural fibres of interest to developing countries is the sisal fibre. The Agave plant from which it is relatively easily extracted and processed can be, and has been, grown in most tropical countries. Unfortunately, as reported by Swift and Smith (1979b), for sisal producing countries, their export markets are in decline due to competition from synthetic fibres. This have tended to replace sisal in many different forms of applications such as in "bag and Cordage Industry" where items made include sisal mats, sacks, cloth, ropes and the pulp for paper (Swift and Smith, 1979b). Due to this competition, production of sisal fibre in these countries has tended to go down with time as many plantations have reduced their production capacities or finally closed down (Kirima and Mutuli, 1990).

Due to the reasons sighted above, a lot of research has been done to find alternative uses for sisal fibres. One area of interest has been to use the fibre for reinforcement in cement based materials.

Swift and Smith (1979a) reported that, long sisal fibres reinforcement of mortar improves the flexural strength by more than a factor of 3, the fracture toughness by a factor of 7 and impact strength by a factor greater than 7. It was also reported that chopped fibres are less effective in this respect raising the flexure strength of mortar by at most 50% and fracture toughness and impact energy by at most 100%.

Swift and Smith (1979b) again presented a theoretical model for flexural behaviour of a cement-based composites reinforced with low modulus fibres. The model predicted large increases in the flexural strength of such composites under certain conditions.

Mutuli (1979) reported that, sisal fibres have very promising mechanical properties as compared to other natural fibres (see Tables 8.1 and 8.2). He also reported on the reinforcement of roofing sheets with the sisal fibre using cement paste as a matrix. Considerable improvements on mechanical properties were reported.

Bessell and Mutuli (1982) reported on an experimental method for determining the interfacial bond strength in the sisal cement composite. A reasonable value for the interfacial bond strength was reported.

Mawenya (1983) presented a review of the research work carried out so far in the field of sisal fibre reinforced concrete (SFRC). It was concluded that, the use of sisal and other natural fibres as a reinforcement for brittle materials has many prospects in the development of low-cost housing on a self-reliance basis.

Aziz et al. (1984) reported on the chronological developments, present status,(1984), and future prospects of natural-fibre reinforced concrete in various engineering constructions.

Kirima and Mutuli (1990) found out that reinforcement of mortar with sisal fibres improves the tensile and flexural strengths to reasonable levels.

With the above facts in mind , it was found necessary to study how sisal fibre reinforcement affects the mechanical properties of concrete which is one of the commonly used building materials. Some of the important mechanical properties are; the flexural strength, tensile strength, compressive strength, impact strength, interfacial bond strength, toughness and fracture toughness.

1.1 Objectives

The broad objective of the study was to investigate the effect of sisal fibre reinforcement on the mechanical properties of concrete. The specific objectives were to investigate the effects of the following fibre arrangements on the Flexural Strength, Tensile Strength, Toughness (energy absorption) and Interfacial bond strength.

i) Long and parallel fibres aligned reinforcement
ii) Randomly oriented Short Discontinuous fibre reinforcement
iii) Varying fibre volume fractions for both (i) and (ii) above.

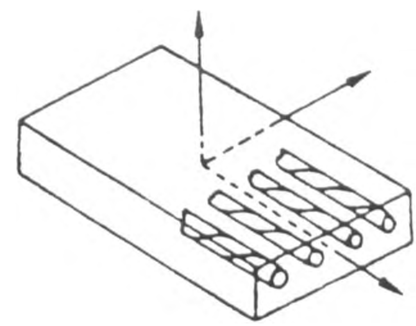
2.0 LITERATURE REVIEW

2.1 Mechanical Properties of Fibre Reinforced Composites

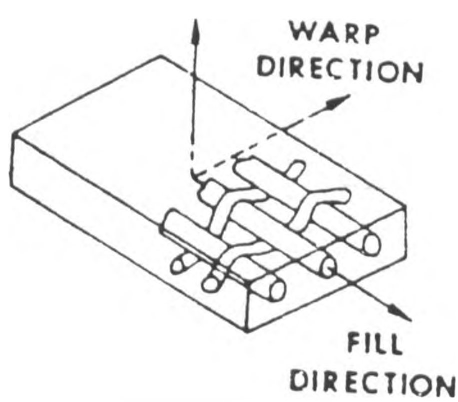
2.1.1 A Three Dimensional Approach to the Elastic Properties of Fibre Reinforced Composites

A lamina is a good example of a simple fibre reinforced composite. Jones (1975) described a lamina as a flat (sometimes curved as in a shell) arrangement of unidirectional fibres or woven fibres in a matrix Figure 2.1 shows examples of laminae along with their principal material axes which are parallel and perpendicular to the fibre directions. The fibres, or filaments, according to Jones (1975) are the principal reinforcing or load-carrying agents. They are typically strong and stiff. The matrix can be organic, ceramic, or metallic. The function of the matrix is to support and protect the fibres and to provide a means of distributing load among and transmitting load between the fibres.

A stack of laminae with various orientations of principal material directions as shown in Figure 2.2 forms a laminate. The layers of a laminate are usually bound together by the same matrix material that is used in the laminae.



LAMINA WITH
UNIDIRECTIONAL FIBERS



LAMINA WITH
WOVEN FIBERS

Figure 2.1. Two principal types of laminae

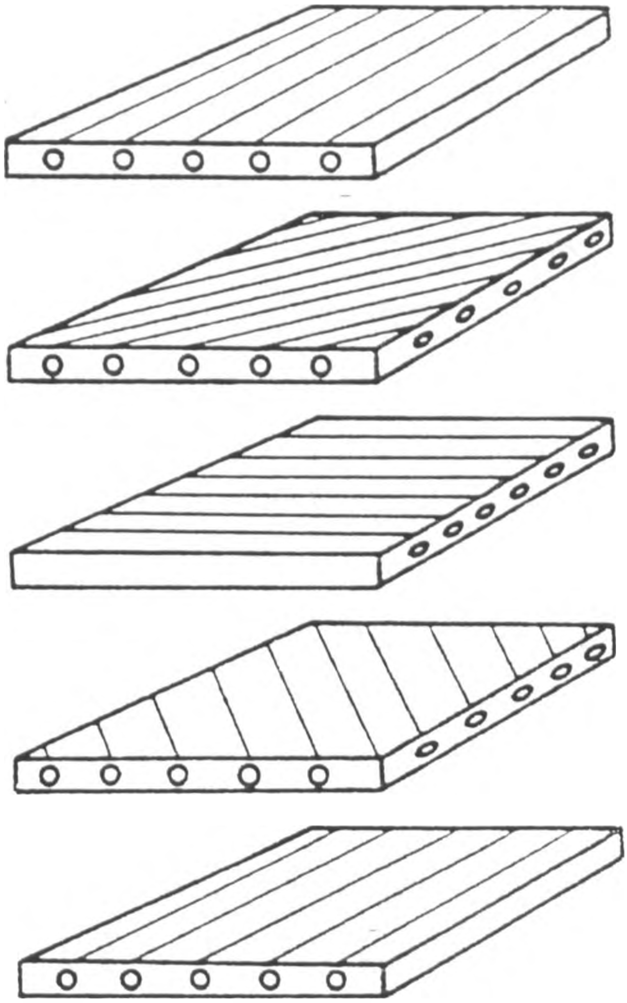


Figure 2.2. Laminate Construction

2.1.1.1 Elastic properties of a Unidirectional Lamina

Several authors have came up with relations describing the elastic properties of a lamina. Jones (1975) and Hull (1990) based their arguments on the following assumptions:

(a) the fibre reinforced composite (FRC), is macroscopically homogenous, linearly elastic, orthotropic and initially stress free

(b) the fibres are, homogeneous, linearly elastic, isotropic, regularly spaced and perfectly aligned.

(c) the matrix is homogeneous, linearly elastic and isotropic

and in addition, no voids can exist in the fibres or matrix or between them (i.e. the bonds between the fibres and matrix are perfect).

Hull (1990) states that, the stresses at a point in a solid can be represented by the stresses acting on the surface of a cube at that point using the notations shown in Figure 2.3. There are three normal stresses σ_{11}, σ_{22} and σ_{33}, and three shear stresses τ_{23}, τ_{31} and τ_{12}. A number of different notations can be used to represent the stresses and strains, for example, a contracted notation replaces σ_{11}, σ_{22}, σ_{33}, τ_{23}, τ_{31} and τ_{12} by σ_1, σ_2, σ_3, σ_4, σ_5 and σ_6 and similar with the corresponding strains e.g. ϵ_{11} etc. Nine stress components must be used to define the state of stress at a point, namely σ_1, σ_2, σ_3, τ_{23}, τ_{31}, τ_{12}, τ_{32}, τ_{13} and τ_{21}.

Therefore Hooke's law can be expressed in a generalized form, using the contracted notation (Hull, 1990) as:

$$\sigma_i = C_{ij}\epsilon_j \qquad \text{...(2.1)}$$

where i,j = 1 .... 6. The σ are the stress components and ϵ are the strain components. C_{ij} is called the stiffness matrix. It can be shown that $C_{ij} = C_{ji}$ so that in

expanded form, Equation (2.1) becomes:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} \qquad \text{...(2.2)}$$

where: σ = Normal Stress, τ = Shear Stress,

ϵ = Normal Strain and γ = Shear Strain

which is the matrix notation for six equations relating stress to strain, the first two being:

$$\sigma_1 = C_{11}\epsilon_1 + C_{12}\epsilon_2 + C_{13}\epsilon_3 + C_{14}\gamma_{23} + C_{15}\gamma_{31} + C_{16}\gamma_{12}$$

$$\sigma_2 = C_{12}\epsilon_1 + C_{22}\epsilon_2 + C_{23}\epsilon_3 + C_{24}\gamma_{23} + C_{25}\gamma_{31} + C_{26}\gamma_{12}$$

...(2.3)

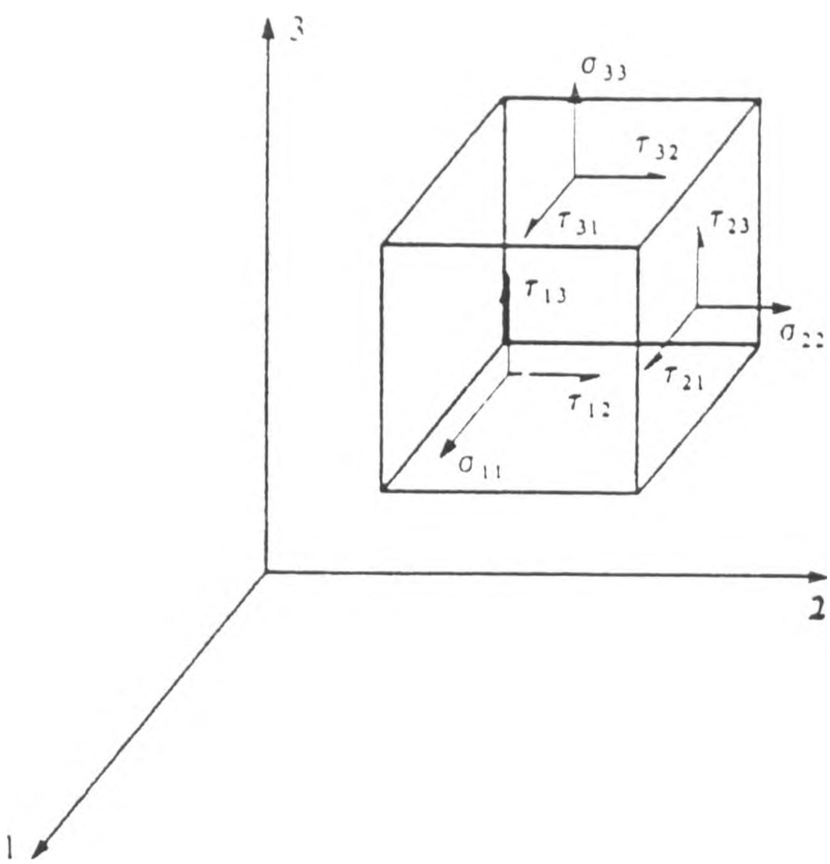


Figure 2.3. Components of stress acting on an elemental unit cube.

For isotropic materials the stiffness matrix is much simpler because the elastic properties are the same in all directions and therefore Equations (2.2) reduces to:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2}(C_{11}-C_{12}) & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2}(C_{11}-C_{12}) & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}(C_{11}-C_{12}) \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} \quad \ldots(2.4)$$

There is a corresponding set of Equations which relate strain to stress:

$$\epsilon_i = S_{ij}\sigma_j \quad \ldots(2.5)$$

where S_{ij} is the compliance Matrix.

For an Isotropic material this equation reduces to

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{12} & 0 & 0 & 0 \\ S_{12} & S_{11} & S_{12} & 0 & 0 & 0 \\ S_{12} & S_{12} & S_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(S_{11}-S_{12}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(S_{11}-S_{12}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(S_{11}-S_{12}) \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} \quad \ldots(2.6)$$

The compliance matrix can be expressed in terms of the Engineering Constants and Equation (2.6) would become:

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} \qquad \ldots(2.7)$$

where E and G are elasticity and shear modulus respectively

For simple uniaxial tensile test, $\sigma_1 = \sigma$ and $\sigma_2 = \sigma_3 = \tau_{23} = \tau_{31} = \tau_{12} = 0$. , therefore Equation (2.7) reduces to:

$$\epsilon_1 = (1/E)\sigma \qquad \ldots(2.8)$$

which is a simple form of Hooke's law.

2.1.2 Continuous Fibre Composites

According to Hollaway (1989), when the fibres are unidirectionally aligned in the matrix material, the composite will possess orthotropic properties with the greatest stiffness and strength in the direction of the fibre. Its properties will depend upon the fibre volume fraction and the mechanical properties of the component parts, and the elastic properties of the composites may be expressed as:

$$E_c = fn(E_f, V_f, E_m, V_m, \nu_m) \qquad \ldots(2.9)$$

Where E_c is the elastic modulus of the composite, E_f and V_f are the elastic modulus and volume fraction of the fibres respectively, E_m and V_m are the elastic modulus and volume fraction of the matrix respectively, ν_m = Poisson's ratio of the matrix and 'fn' stands for function.

2.1.3 Stiffness of a Composite

For efficient stress transfer to the fibre, the elastic modulus of the matrix must be very much lower than that of the fibre (Swamy, 1974). It therefore follows, that there is a minimum modular ratio

$$\frac{E_{fibre}}{E_{matrix}} \geq 1$$

below which improvement in the mechanical strength properties of the composite cannot be obtained. According to Swamy (1974), high strength, high Modulus fibres impart strength and stiffness to the composites, whereas low Modulus, high elongation fibres would result to large energy absorption characteristics and impart toughness and resistance to impact and explosive loading.

Hollaway (1989) stated that, to determine the value of the modulus of elasticity of the composite E_c, in the fibre direction, it is assumed that:

(a) The load carried by the composite is the sum of the loads carried individually by the matrix and the fibre with both matrix and fibre acting together as a two phase composite until failure.

(b) The strains in the matrix and fibre remain the same and is given by the rule of mixtures :

$$E_c = E_m V_m + E_f V_f \qquad \text{...(2.10)}$$

2.1.3.1 The Poisson's Ratio ν_{12}

The rule of mixtures (Equation 2.10) has been extended to predict the Poisson's ratio of a composite reinforced with continuous fibres with a fair degree of accuracy as given by Hollaway (1989) as:

$$\nu_{12} = \nu_f V_f + \nu_m V_m \qquad \text{...(2.11)}$$

2.1.4 Uniaxial Tension

The rule of mixtures (Equation 2.10) may also be modified to approximate the composite stress σ_c in terms of fibre volume fraction V_f and stress induced in the matrix σ_m and fibre σ_f as reported by Hollaway (1989):

$$\sigma_c = \sigma_f V_f + \sigma_m (1-V_f) \qquad ...(2.12)$$

According to Hollaway (1989), in most practical cases, σ_m and σ_f do not occur at the same time as Equation (2.12) suggests and therefore Equation (2.12) can be modified accordingly depending on the one that occurs first.

In the case where the matrix fractures first as in a brittle matrix, with low failure strains (like cement base materials) Equations (2.12) is slightly modified to:

$$\sigma_c = \sigma_f' V_f + \sigma_m (1-V_f) \qquad ...(2.13)$$

where σ'_f is the stress in the fibres at the failure strain of the matrix.

In case where the fibre fails first (typical of a carbon fibre-epoxy matrix system) Equation (2.12) becomes:

$$\sigma_c = \sigma_f V_f + \sigma_m' (1-V_f) \qquad ...(2.14)$$

where σ'_m is the stress in the matrix at the failure strain of the fibre.

2.1.4.1 Post-cracking behaviour in tension

Keer (1984) reported that in the case of a brittle matrix (like cement), once the matrix cracks, three types of behaviour in tension may be exhibited by a fibre cement or concrete as shown in Figure 2.4 (a, b,c).

(a) The composite fails as fibres fracture under the increased stress applied to them (Figure 2.4a).

(b) The composite can carry a decreasing load as the fibre pull-out from the cracked surface (Figure 2.4b). No increase after matrix cracking, of the tensile strength of the composite is observed yet the strain at complete failure is increased and there can be a considerable increase in the toughness of the composite as measured by the area under the complete load-deflection curve. This type of behaviour is typical of some short randomly oriented steel or organic fibre composites (Keer, 1984).

(c) The composite continues to carry an increasing tensile stress and multiple cracking of the matrix occurs. Cement base materials may

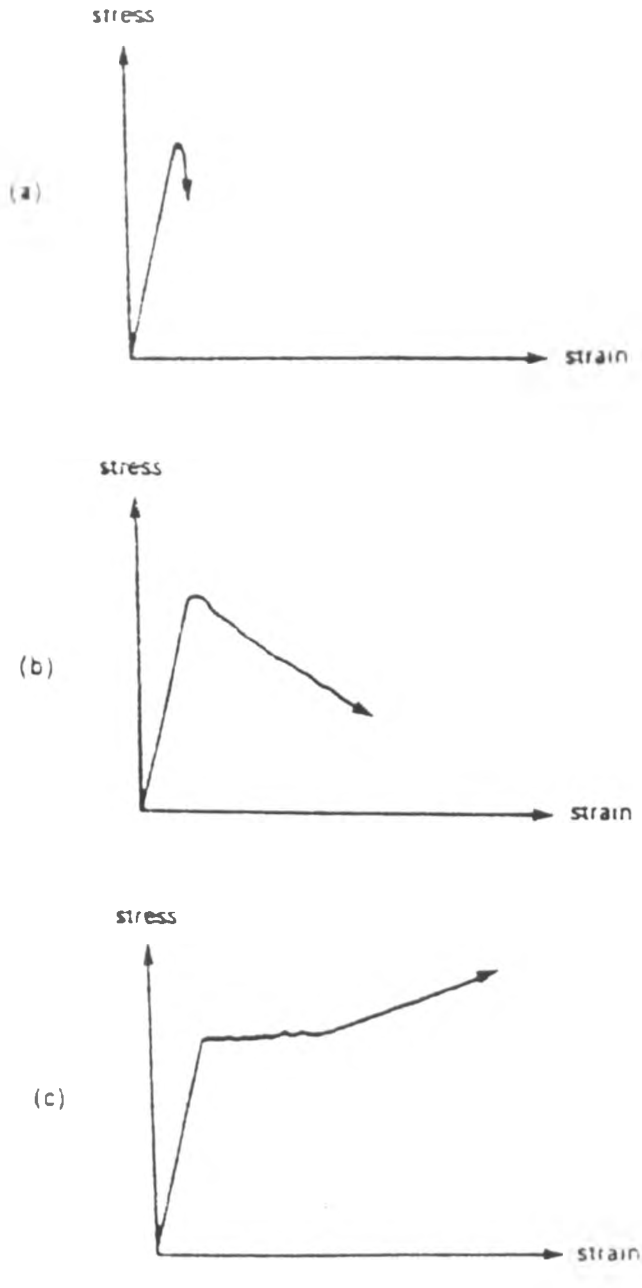


Figure 2.4. Types of behaviour in tension exhibited by fibre cements or concrete : (a) composite fails when matrix cracks; (b) composite carries a decreasing load as fibres pull out at crack; (c) composite can carry an increasing load after matrix cracking (Keer 1984).

exhibit this type of behaviour when reinforced with a sufficient volume of continuous (long) fibres (Figure 2.4c).

For multiple cracking to occur, according to Keer (1984), the fibre volume fraction must be greater than a critical value given by:

$$V_{fcrit.} = \frac{E_c \epsilon_m}{\sigma_f} \qquad \ldots(2.15)$$

where ϵ_m is the strain at which the matrix cracks and σ_f is the failure stress of the fibres or the stress which causes the fibre to pull out of the matrix.

According to Nicholls (1976) and Moore (1967) , in the cases where the fracture strain of the fibres is less than that of matrix, the critical volume fraction is given as

$$V_{fcrit} = \frac{\sigma_u - \sigma'_m}{\sigma_f - \sigma'_m} \qquad \ldots(2.16)$$

where σ_u is the tensile strength of the matrix, σ'_m is the matrix stress at the instant of fibre fracture and σ_f is the tensile strength of the fibre. According to Forsyth (1965) the minimum volume fraction is given as:

$$V_{min} = \frac{\sigma_u - \sigma_m'}{\sigma_f + \sigma_u - \sigma_m'} \qquad ...(2.17)$$

According to Nicholls (1976), the mode of fracture in a fibre reinforced composite is influenced by the relative magnitudes of failure strengths and strains of matrix and fibre. Single modes of fracture are normally seen in matrices that have similar magnitudes of strains as that of the reinforcing fibre or where the failure strain of fibre is less than that of matrix, the onset of fibre failure leads to composite failure as the matrix cannot withstand the load alone.

The behaviour is however different in the case of brittle matrices reinforced with fibres of relatively greater breaking strains. Provided that there are sufficient fibres to support the load after the matrix has failed, the composite fails exhibiting multiple cracking mode of failure, with the composite behaving in a Pseudo-ductile fashion. The critical fibre volume fraction which has to be exceeded for this to take place is defined by the inequality below presented by Aveston et al (1974).

$$\sigma_{fu} V_f \quad > \quad E_c \, \epsilon_m \qquad ...(2.18)$$

where: σ_{fu} is the fibre fracture strength, V_f is the fibre volume fraction, E_c is the composite modulus derived from the rule of mixtures and ϵ_m is the matrix failure strain.

When V_f is lower than the critical volume fraction, the composite will fail in a single fracture mode.

Therefore according to Aveston et al (1971), multiple Cracking would take place if:

$$\sigma_f V_f \quad < \quad (\sigma_f V_f + \sigma_m V_m) \qquad \text{...(2.19)}$$

and single Crack failure mode when

$$\sigma_f V_f \quad < \quad (\sigma'_f V_f + \sigma_m V_m) \qquad \text{...(2.20)}$$

where σ'_f is the fibre stress at the failure strain of the matrix.

Multiple fracture will continue until final fracture takes place when fibres fracture and the ultimate composite strength is given by:

$$\sigma_{cu} = V_f \, \sigma_f \qquad \text{...(2.21)}$$

2.1.5 Flexural Strength of Concrete Reinforced with Randomly Oriented Short Discontinuous Fibres

Swamy et al. (1973) presented a combined crack control composite materials approach to predict the first crack modulus of rapture and the ultimate modulus of rapture of concrete reinforced with randomly oriented short discontinuous fibre. In steel fibre reinforced concrete, the composite failure generally occurs due to bond failure at the fibre matrix interface. The first crack in the composite occurs when the composite strain exceeds the cracking strain of the matrix. On further loading, the stiffer fibres act as crack arrestors, analogous to coarse aggregates in plain concrete, and a period of slow crack propagation with progressive debonding of fibre occurs. Near the ultimate load, unstable crack propagation occurs simultaneously with the interfacial bond reaching the ultimate bond strength (τ_u) between the fibre and the matrix and failure by fibre pull-out occurs (Swamy et al., 1973).

Thus according to Swamy et al. (1973), composite fracture occurs simultaneously due to unstable crack propagation and bond failure. Both the matrix and the fibre act together as a two-phase composite until failure and contribute to the strength of the composite.

Swamy et al (1973) reported that fibres do not make full contribution to the composite strength, because, due to the bond failure, the maximum tensile stress σ_f in the fibre is less than its ultimate strength σ_{fu}.

Using the law of mixtures as a basis, Swamy et al. (1973) derived the following expression for the flexural strength of concrete reinforced with randomly oriented short steel fibres.

$$\sigma_{fc} = A\,\sigma_m(1 - V_f) + 0.82\,\tau\,V_f(L/d) \qquad \ldots(2.22)$$

where σ and V represent stress and volume respectively, and suffixes c, m and f represent composite, matrix and fibre, respectively.

By regression analysis of a wide range of flexural strength data, Swamy et al (1973) obtained the following Equations:

First crack composite flexural strength.

$$\sigma_{cf1} = 0.843\,\sigma_m\,(1-V_f) + 2.93\,V_f\,L/d \qquad \ldots(2.23)$$

Ultimate composite flexural strength:

$$\sigma_{fcu} = 0.97\sigma_m(1-V_f) + 3.41 V_f L/d \qquad \ldots(2.24)$$

Mangat and Gurusamy (1987) from more research modified Equations (2.23) and (2.24) to:

$$\sigma_{fc1} = 0.82\sigma_m(1-\beta V_f)+2.7V_fL/d \qquad ...(2.25)$$

and

$$\sigma_{fcu} = 0.97\sigma_m(1-\beta V_f)+3.41V_fL/d \qquad ...(2.26)$$

respectively. Where ß stands for fibre orientation factor.

2.1.6 Fibre - Matrix Interfacial bond

The interfacial bond between the matrix and the fibre determines the effectiveness of stress transfer from the matrix to the fibre. Swamy and Mangat (1976) reported that, in Civil Engineering practice, the steel fibre composite is often in a state of flexure and that de-bonding of the fibre occurs in flexural tension in the presence of a straight gradient. The authors computed interfacial bond stress indirectly from a wide range of flexural strength results.

Swamy and Mangat (1976) used the Aveston's method which states that, for concrete mixes reinforced with short discrete fibres randomly oriented, free from balling or curling and uniformly distributed throughout the matrix, the flexural strength σ_{fc} of the steel fibre composite is given by:

$$\sigma_{fc} = A\sigma_m(1-V_f)+0.82\tau V_f(L/d) \qquad ...(2.27)$$

Where σ_m is the flexural strength of the matrix, V_f is the volume fraction of the fibre of length L and diameter d, and τ is the average fibre-matrix interfacial bond stress. Swamy and Mangat (1974) reported that, the constant A and the interfacial bond stress τ involve the relationship between the direct tensile strength and the flexural strength.

Equation (2.27) can be rewritten as

$$\frac{\sigma_{fc}}{V_f\ (\frac{L}{d})} = A\ \frac{\sigma_m\ (1-V_f)}{V_f\ (\frac{L}{d})} + 0.82\tau \qquad ...(2.28)$$

A graph of $\sigma_{fc}/V_f(L/d)$ against $\sigma_m(1 - V_f)/V_f(L/d)$ should produce a straight line. The interfacial bond strength can be obtained from the y-axis intercept and the constant A from the gradient (Swamy and Mangat, 1976).

Bessell and Mutuli (1982), Baggot and Gadhi (1981) and Kirima and Mutuli (1990), have used an expression proposed by Aveston et al (1971) for the interfacial bond strength for uniaxially reinforced composites. The basis of the equation is that, in brittle matrix composites reinforced with ductile fibres, the tensile fracture will take place by multiple cracking of the matrix in the direction normal to the applied load. The ductile fibres will initially bridge the cracks by taking up all the load and will eventually fail themselves. In this case it was shown that the interfacial bond strength τ may be obtained from the following Equation:

$$x = \frac{(1-V_f)}{V_f} \cdot \frac{\sigma_m r}{2\tau} \qquad \ldots(2.29)$$

Where V_f is volume fraction of fibre, σ_m is the tensile strength of the matrix, r is the fibre radius, x is the crack spacing and τ is the interfacial bond strength.

From Equation 2.29, a plot of x against $(1-V_f)/V_f$ produces a straight line passing almost through the origin and the bond strength (τ) can be obtained from the gradient.

Aveston et al (1971) showed that multiple cracking of a matrix would occur provided that:

$$\sigma_{fu} V_f > (\sigma_m V_m + \sigma'_f V_f) \qquad \ldots(2.30)$$

where σ_{fu} is the fibre ultimate stress, V_m is the volume fraction of matrix and σ'_f the fibre stress at onset of cracking.

2.1.7 Critical Fibre length

The law of mixtures has also been extended to predict the composite strength and modulus of elasticity for randomly oriented chopped fibres. The effectiveness of short fibres in load transfer in a fibre reinforced composite relies to a greater extend to a perfect bond strength between the fibre and the Matrix (Mutuli, 1979).

Kelly (1965) introduced the concept of the critical fibre length on which complete stress transfer takes place between the fibre and the matrix. For fibres shorter than the critical length, failure is by pull-out and the full strength of the fibre is not realized. On the other hand fracture of fibres takes place for lengths greater than critical length as the matrix grips the fibres over a good length. This principle is expressed in the relationship.

$$L_c = \frac{\sigma_f d}{2\tau} \qquad \ldots(2.31)$$

where L_c is the critical length, d is the fibre diameter, σ_f is the fibre tensile strength and τ is the interfacial bond strength between the fibre and matrix. The load is transferred from the matrix to the fibre by shear at the interface over a distance $L_c/2$.

Swamy et al. (1973) further reported that, L_c depends on τ and if bond failure occurs, τ will then represent the frictional force per unit area between matrix and fibre. The frictional force, according to Swamy et al (1973), may be adequate to impart to the composite a measure of ductility, crack resistance and toughness. The fibre tensile strength is also not constant along the length and therefore the average stress must be used instead of σ_f. The average fibre stress over the length L_c is $\sigma_f/2$ (assuming linear distribution), but if the fibres are longer than L_c, the average stress will approach the maximum σ_f, and the fibre will effectively act as continuous fibre.

According to Parameshwaran and Rajagopalan (1975), the stress is given by:

$$\sigma_c = C \ \sigma_f V_f + \sigma_m(1-V_f) \qquad \text{...(2.32)}$$

Where C = (2L - Lc)ß / 2L

ß = is the orientation factor

Romualdi and Mendel (1964) calculated the orientation factor as 0.41 while Parimi and Rao (1973) came up with two values of 0.5 and 0.64 and they argued that values greater than 0.5 are more practical.

For fibre lengths much greater than the critical length, the efficiency factor tends to unity while in the case of chopped fibres uniaxially aligned, the orientation factor is equal to one (i.e. $\beta = 1$). composites with discontinuous fibres not aligned in the stress direction result in lower strength values in comparison with discontinuous aligned fibres (Mutuli, 1979).

2.1.8 Effective Fibre Spacing for Short Discontinuous Fibres

Parimi and Rao (1973) derived an expression for the average spacing for random fibres S, in any matrix. A uniform distribution of fibres throughout the matrix was assumed and the length L, of the fibres was assumed same for all fibres. The following equation was obtained:

$$S = 5\frac{\sqrt{\pi}}{\beta}\frac{d}{\sqrt{P}} \qquad \text{...(2.33)}$$

where P = Percentage of fibre by volume

d = diameter of fibre

ß = Orientation factor of the fibre (for continuous fibres, ß = 1)

Swamy et. al (1973) derived expressions for the effective spacing for first crack modulus of rapture and ultimate modulus of rapture as:

For first crack modulus of rapture

$$S_e = 27\frac{\sqrt{d}}{PL} \qquad \text{...(2.34)}$$

and for Ultimate Modulus of rapture

$$S_e = 25\frac{\sqrt{d}}{PL} \qquad \text{...(2.35)}$$

where S_e = effective spacing

L = fibre length

2.1.9 Toughness

A considerable increase in toughness is also imparted by fibre reinforcement. Shah and Rangan (1971) and Blood (1970) defined toughness as the area under the complete load-deflection curve including the descending portion. Johnston (1971) argues that, this definition of toughness, in terms of the serviceability of a structural unit, has little practical significant because deflections and crack widths far exceed the normally acceptable limits. He points out that, toughness defined as the area under the load-deflection curve up to the maximum flexural stress obtained, or up to a specified deflection representing the degree of cracking allowable in service, is more meaningful from the point of view of serviceability of the unit.

2.1.9.1 Fracture Toughness

Concrete matrix like other brittle materials is weak in tension with low ductility and little resistance to impact loading. It has very low fracture toughness and this is due to the mode of fracture which is brittle. Fibre reinforcement of concrete increases the fracture toughness tremendously because a lot of energy is absorbed in trying to fracture the fibre-Matrix interfaces (Mutuli, 1979).

A number of energy absorbing Mechanisms take place during the failure of such composites. These are matrix fracture, fibre fracture, bond failure and fibre pull-out accounting for the total fracture toughness of the composites (Mutuli, 1979). Equations to predict the energy absorbed for different forms of failure have been developed by different authors. Cooper and Kelly (1967) proposed the following

Equations:

$$G_m = \frac{V_m^2 \sigma_m \gamma U_m}{2 V_f \tau} \qquad \ldots(2.36)$$

where U_m is the work done to deform a unit volume of matrix to failure. The work done in fracturing the fibre as given by Bessell (1973) is given by:

$$G = \frac{V_f \sigma_f^2 L_c}{6 E_f} \qquad \ldots(2.37)$$

Other energy absorbing mechanisms as listed by Dharan (1978) are:

(a) Fracture energy due to debonding of fibres

$$G = \frac{\sigma_f^2 \gamma}{2 V_f E_f \tau} \left[\frac{\sigma_f}{V_f} - \frac{(4 G_{11} E_f)^{\frac{1}{2}}}{\gamma} \right] \qquad \ldots(2.38)$$

Where G_{11} is the bond strength.

(b) Fracture energy due to pull-out of fibres

$$G = \frac{L_c V_f \tau L_c^2}{24 L \gamma} \qquad for \quad L > L_c \qquad \ldots(2.39)$$

or

$$G = \frac{V_f \tau L^2}{24\gamma} \qquad for \quad L < L_c \qquad \ldots(2.40)$$

2.2 Water

Water used for concrete mixtures should contain no substance which can have an appreciably harmful effect upon strength (i.e., upon the process of hydration of the cement, or upon durability of the concrete in service). According to Troxell (1968), water that is acceptable for drinking purposes is satisfactory for use as a mixing water, for washing aggregates and for curing. Water from streams, not subject to contamination by domestic wastes, and does not have a brackish or salty taste is also acceptable.

Substances which, if present in sufficient amounts in the water used, may have an injurious effect upon concrete are silt, oil, acids, alkalies and salts of alkalies, organic matter, and sewage. Sources of supply which should be regarded with suspicion are streams carrying large concentrations of suspended solids, streams carrying industrial and domestic wastes, small streams and wells in mining country (acid mine waters), and wells, small lakes, and small streams in arid alkali country (Troxell, 1968).

3.0. METHODOLOGY

3.1 Introduction

The effect of sisal fibre reinforcement on concrete for both chopped fibres randomly reinforced and long and parallel fibre reinforcement were examined under varying fibre reinforcement volume fractions. This was done by looking at the following properties:

- (a) Flexural strength
- (b) Tensile strength
- (c) Toughness (energy absorption before complete failure)
- (d) Fibre-Matrix interfacial bond strength.

In order to do this, two types of tests were done on concrete samples reinforced with sisal fibres.

3.2 Description and Preparation of Materials

The materials for this study included; Cement, aggregate (Sand, Ballast), Sisal fibres, and Water.

The cement used was ordinary portland cement from Athi River Portland Cement factory, Kenya. The sand was river sand and was made to pass through a 2mm sieve. The ballast was crushed stone and was made to pass 10mm sieve in order to obtain a maximum ballast size of 10mm. Both the sand and Ballast were put in an oven for 12 hours at 105°c and left to cool to room temperatures for 12 hours before use.

The sisal fibres used in this study were grade "UG" from Taita Sisal estates, Kenya with mechanical and physical properties as given in Table 8.1 (Mutuli, 1979). The water was ordinary clean treated tap water.

The concrete mix used throughout the study for all samples was 1:2:2.5 (1 part cement, 2 parts sand and 2.5 parts ballast), and a water/cement ratio of 0.5. The mix was designed to have a minimum crushing strength of 30 MPa. for 28-day cubes (i.e. concrete grade C30 according to the British Standard BS 5328: 1976).

3.3 Sample Preparation

3.3.1 Preparation of Cube samples for Crushing strength determination

The concrete mix was designed to have a crushing strength of 30 MPa and above. In order to confirm this, four cubes were casted according to British Standard specifications. The dimensions of the Cubes were 152 mm by 152 mm by 152 mm.

3.3.2 Flexural Strength Samples

3.3.2.1 Chopped fibre randomly reinforced Samples

Flexure beams of dimensions 100 mm by 100 mm by 510 mm were prepared according to the British Standard specifications

(BS 1881: part 118: 1983). Steel moulds were used and Mould oil was smeared on the inside surfaces of the moulds to avoid sticking. A known weight of the chopped fibres was mixed well with weighed amount of the concrete (mix 1:2:2.5) of water/cement ratio of 0.5. The mixture was placed in the mould and vibrated for three minutes to expel entrapped air and obtain good compaction. The surface of the mould was finished well by use of a masons trowel. The mould was covered with moist hessian cloth for 24 hours before stripping and storing the test specimens in water for curing. For every fibre content, three replicates were tested.

3.3.2.2 Long and Parallel fibre reinforced samples

Bending beams of dimensions 100 mm by 100 mm by 510 mm were prepared according to the British Standard Specifications (BS 1881: Part 118: 1983). Steel moulds were smeared with mould oil on the inside to avoid sticking. Little amount of concrete that had been prepared was put in the mould and spread nicely. This concrete was vibrated slightly to ensure a level surface. Sisal fibres cut to the length of 500 mm were weighed, enough for every mould and corresponding to the required fibre volume fraction. A layer of the fibres was spread in the mould on top of the concrete. Another layer of concrete was spread in the mould and vibrated slightly. This addition of a layer of concrete followed by a layer of fibre was continued until the mould was filled. Three replicates were prepared for every fibre fraction.

The moulds were then vibrated for three minutes in order to expel the entrapped air and obtain good compaction. The top surface was then finished well by use of a Masons trowel. The samples were then covered with moist hessian cloth for 24 hours before stripping the moulds and storing the samples in water for curing.

3.3.3 Tensile strength test samples

These were prepared the same way like those for flexural strength for both chopped fibres randomly reinforced and long and parallel fibre reinforced samples with difference only in dimensions. The dimensions for the Tensile strength samples were 80 mm by 80 mm by 400 mm long. Wooden moulds were used and Plasticine was used to make the joints watertight. Three replicates were prepared for every fibre volume fraction.

3.4 Unreinforced specimens

Unreinforced flexure and tensile specimens were cast using the same moulds as for reinforced specimens. The same casting procedure was followed although in this case no fibres were embedded.

3.5 Curing and Transportation of Samples

All the samples were cured in water for 28 days before testing. The water used for curing was clean treated water fit for human consumption. The casting and curing was done in the concrete Laboratory of the Department of Civil Engineering, University of Nairobi, Kenya. The testing was done in the Mechanical Testing Laboratory of the Kenya Bureau of Standards. During the transportation to the testing Laboratory, every sample was wrapped with a dump hessian cloth before being placed in a pick-up vehicle. At the testing Laboratory, sample were again put into a curing tank and then tested serially.

3.6 Testing of Samples

3.6.1 Testing for Crushing Strength (Compression)

Cubes cast as described in section 3.3.1 were tested for compressive strength according to the British Standard specifications. These were loaded in compression at a strain rate of 0.066 per minute until failure and the maximum load recorded. The compressive strength tabulated results were as given in Table 4.1.

3.6.2 Testing for Flexural Strength

Beams casted for flexural tests as described in Sections 3.3.2.1 and 3.3.2.2 were tested for bending strength according to the British Standard specifications (BS 1881:

part 118: 1983). The loading arrangement was as given in Figure 3.1 and Plates 8.4 and 8.9 show pictures of the bending test apparatus and failure modes.

The Universal testing machine was used and a loading speed of 10 mm per minute was maintained for all the samples. A graph of load against extension during loading was obtained from the machine directly.

The flexural strengths were later calculated from values obtained from the load-extension graphs and these are as given in Table 4.2 and 4.3.

3.6.3 Testing for Tensile Strength

Beams cast as described in section 3.3.3 were tested in direct tensile test. The splitting tensile test method could not be used due to difficulty of fibre reinforcement. Direct tensile tests are difficult to perform on cement base materials without introducing stress concentrations on the test piece at the point of grip. In this study a gripping arrangement designed by Mutuli (1982) was used (Figure 3.2). This consists of a square top plate with four slots at 90° to each other. Through these slots can be bolted four vertical plates, that are each welded to a vertical bolt (see Figure 3.2), to form an open box section

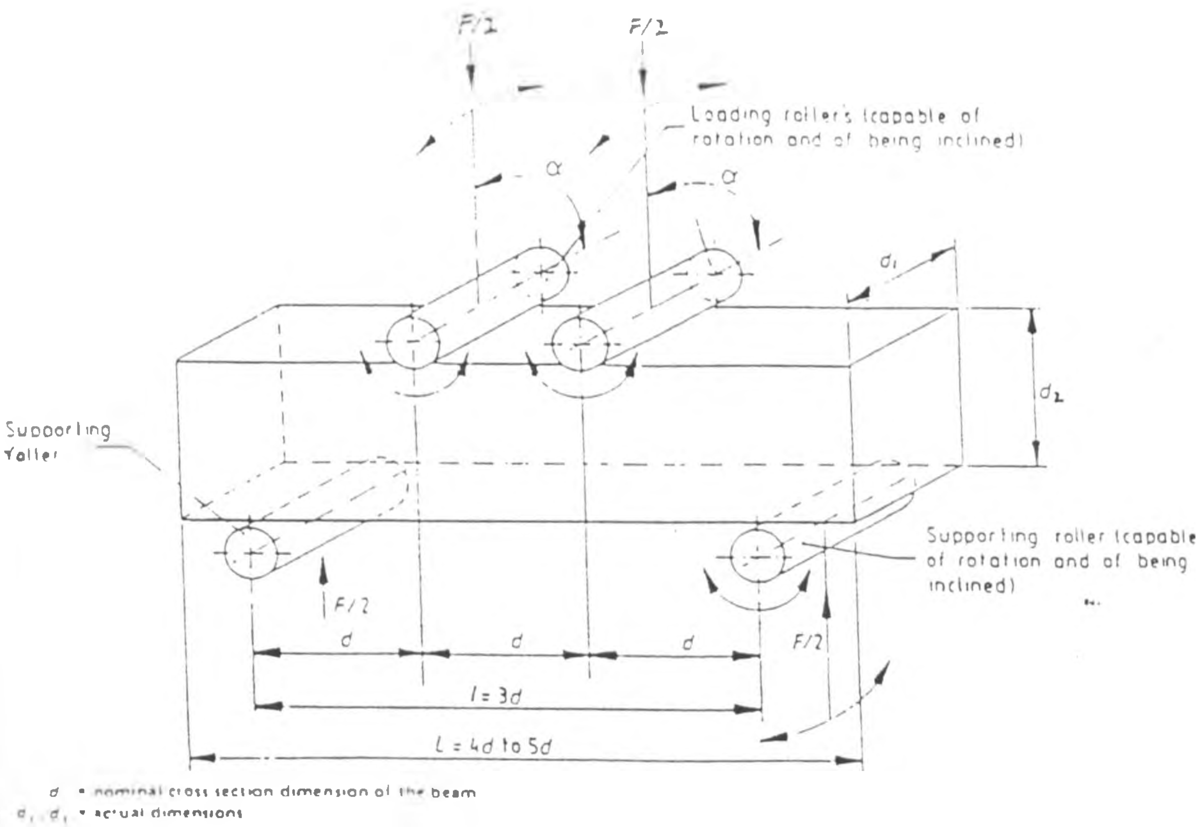


Figure 3.1. Loading arrangement in Bending (four point loading). (BS 1881: Part 118: 1983).

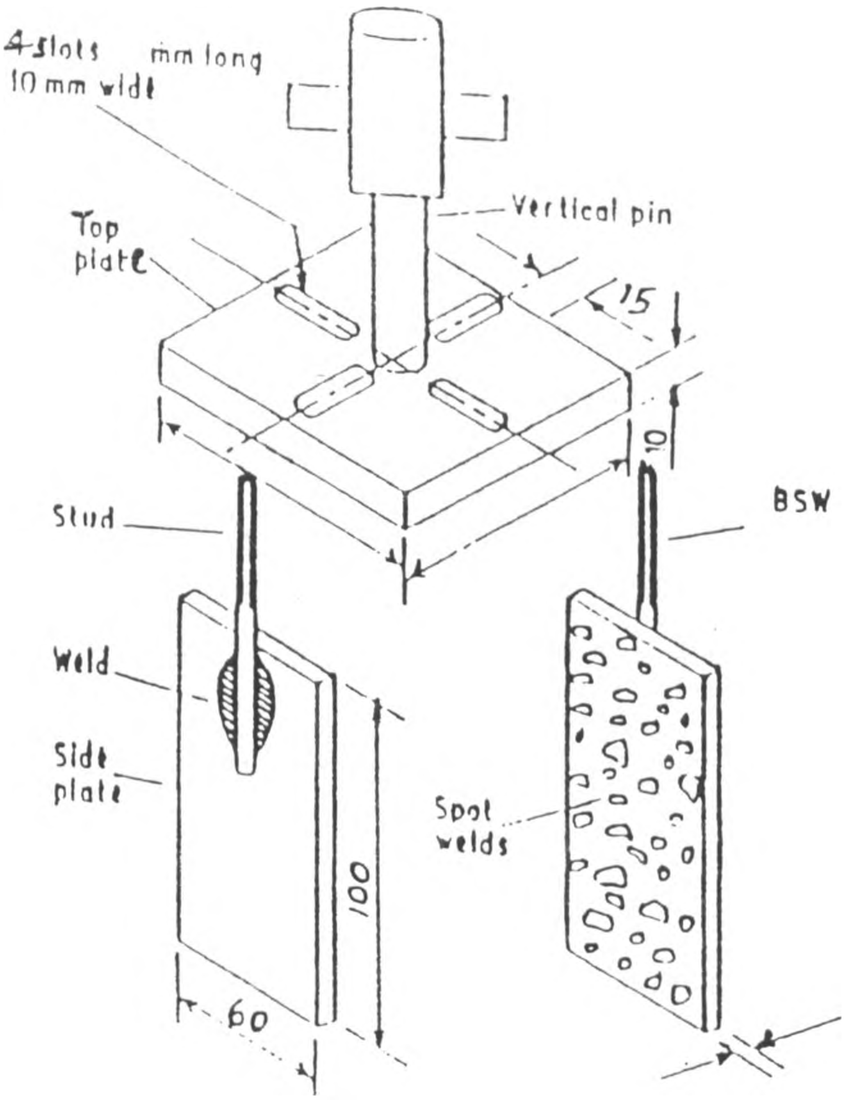


Figure 3.2. Assembly drawing of specimen grips for tensile test showing two side plates. (all dimensions in mm) (Mutuli, 1982).

when in place. The inside surface of these plates were roughened by spot welds to aid in gripping of the specimen. High tensile pins were passed through the top and bottom plates which were gripped by the testing machine.

After curing, the faces of the specimens at the points of gripping were serrated slightly using the power saw blade and glued to the four plates using isopon polyester paste (car body filler). The plates were then held in place using G-clamps. After the isopon paste had set, the vertical plates were bolted into place on the top plate. The upper and lower assemblies were then aligned in a universal testing machine (see Plate 8.7)

During loading, the strain rate was maintained at 0.05 per minute for all test specimens and a graph of load against extension was obtained directly from an attached plotter. The tensile strengths were later calculated from values read from the load-extension graph and these are as given in Tables 4.4 and 4.5.

During the tensile tests for parallel fibre reinforced samples, the crack spacings were measured for every sample at complete failure. The crack spacings were averaged out to obtain an average for every fibre content. This average fibre spacing was used for calculation of the interfacial bond strength (see Table 8.4).

3.7 Data Acquisition

For the two types of experiments performed, graphs of load against extension were obtained directly from the machine during the experiments. Typical load-extension curves are given in Appendix C.

For the strength calculations, maximum loads, reached for both flexural and tensile tests were recorded from the graphs. The results were used for the calculation of the maximum flexural and tensile strengths as given in Tables 4.2 to 4.5.

The following assumptions were made in the calculation of the strength values:

(1) the fibre reinforced composite (FRC), is macroscopically homogenous, linearly elastic, orthotropic and initially stress free

(2) the fibres are, homogeneous, linearly elastic, isotropic, regularly spaced and perfectly aligned.

(3) the matrix is homogeneous, linearly elastic and isotropic

(4) the bonds between the fibres and matrix are perfect.

(5) The load carried by the composite is the sum of the loads carried individually by the matrix and the fibre with both matrix and fibre acting

together as a two phase composite until failure.

(6) The strains in the matrix and fibre remain the same and is given by the rule of mixtures.

The following two equations were used in calculation of the flexural and tensile strengths respectively:

(a) Flexural strength

The Flexural strength f_{cf} (N/mm^2) is given by the Equation:-

$$f_{fc} = \frac{F \times L}{d_1 \times d_2^2} \qquad ...(3.1)$$

Where: F is the breaking load (in N).

d_1 and d_2 are the lateral dimensions of the cross-section (in mm)

L is the distance between the supporting rollers (in mm)

The arrangement is shown in Figure 3.1.

(b) Tensile strength

The Tensile strength (σ_t) was calculated by dividing the maximum load (F) by the cross-sectional area (A). (see Figure 3.3)

$$\sigma_t = F/A \qquad ...(3.2)$$

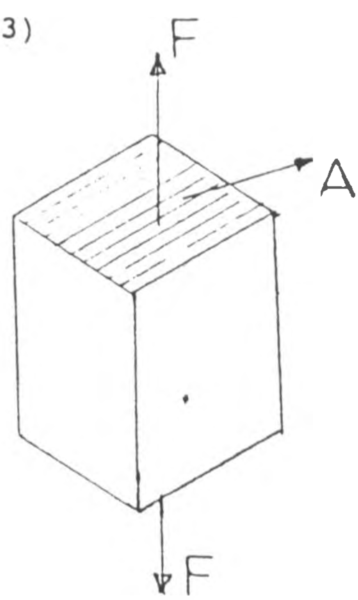


Figure 3.3

The toughness (energy absorption) of the samples was obtained from the area under the load-extension graphs. This was obtained by using a polar planimeter. The calculated values of toughness were presented in Tables 4.6 to 4.9.

4.0 RESULTS AND DISCUSSIONS

4.1 Compressive Strength testing

Table 4.1, gives the results of compression tests. This were done to determine the crushing strength of the concrete mix used. This was found to be 35.49 MPa with a standard deviation of 1.45 MPa. According to Mawenya (1983), in order to achieve the best results for sisal fibre-concrete composites, the concrete mix should be of rather high quality with crushing strength greater or equal to 30 MPa.

Table. 4.1. Compression strength results

Sample	Load (kN)	Strength (MPa)
1	810	35.06
2	787	34.06
3	866	37.50
4	816	35.32

Average crushing strength = 35.49 MPa,
Standard deviation = 1.45 MPa

4.2 Flexural strength tests

Figure 4.1 shows the regression curve for the variation of Flexural strength (FS) with reinforcement fibre volume fraction (V_f) for chopped fibre-concrete samples. The regression equation was obtained as :

$$FS = 5.20 - 0.20V_f - 0.024V_f^2 \quad , \quad R^2 = 0.97 \qquad \ldots(4.1)$$

The strength at 0% fibre volume fraction (V_f) was found from the regression equation to be 5.20 x 10^6 Pa. which compares well with calculated value of 5.04 x 10^5 for 0% V_f. No increment in strength was observed, instead there was progressive decrease in strength with increase in V_f. This could possibly be due to the following reasons:

a) **The fibre length.** According to Mawenya (1983), Sisal fibres can be used for reinforcement as discontinuous chopped short sisal fibres of lengths between 15 and 75 mm. In this study, a length of 15mm was chosen. This was done after few trials with different lengths and the one with the minimum balling-up and curling of the fibres within this range was chosen.

The aspect of critical fibre length reported in section 2.4.7 could have played a big role. The determination of critical fibre length require a knowledge of the interfacial bond strength between the fibre and the matrix. The interfacial bond strength was not known but some attempt was made to determine it using some methods that have worked on previous occasions.

b) **Compaction.** The compaction during casting became harder as more fibres were added and this caused voids to be created which resulted to poor bonding between the matrix and the fibre.

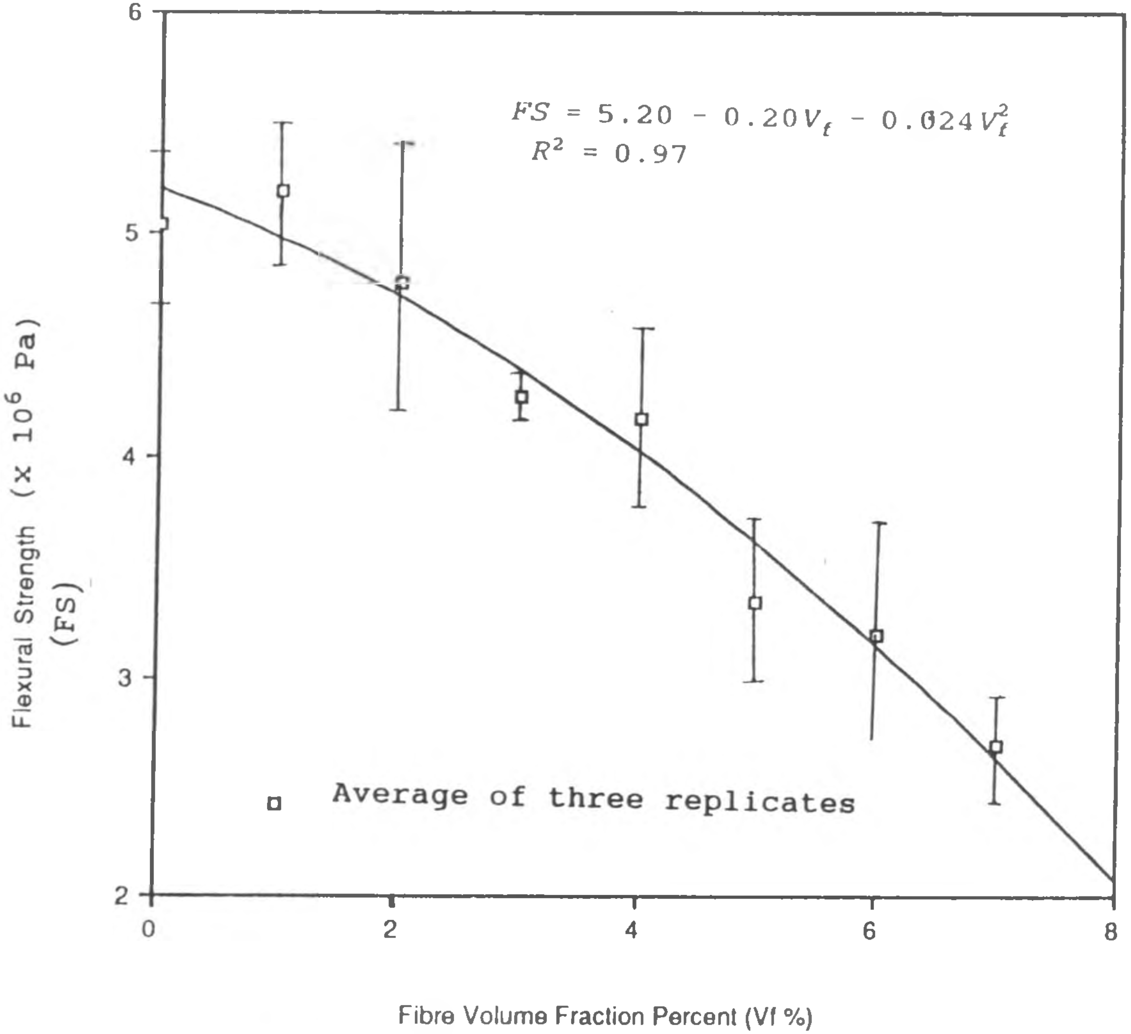


Figure 4.1 : Variation of Flexural strength with reinforcement fibre volume fraction for chopped fibre-concrete composites.

c) **Balling-up and curling of the fibres during mixing.** This problem was observed for chopped fibres and it became more serious at high fibre contents. It was also observed during some trial castings at the beginning that, balling-up increased with fibre length. This balling-up increases the voids which affect the fibre-matrix bond.

d) **The water absorption capacity of the fibres.** The water absorption capacity for sisal fibres is very high. According to Mutuli (1979) and Aziz et al (1984) the water absorption capacity for sisal fibres is between 60-70% . This affects the water-cement ratio which is an important factor in strength of concrete. As the fibre content is increased, it becomes very hard to determine the water-cement ratio required.

A single crack mode of failure was observed for these types of experiment with allot of fibre pull-out.

Figure 4.2 shows the regression curve for the variation of Flexural strength (FS) with reinforcement fibre volume fraction (V_f) for long and parallel fibre-concrete composites. The regression equation was obtained as:

$$FS = 5.21 + 0.51V_f - 0.10V_f^2 \quad , \quad R^2 = 0.66 \quad \ldots(4.2)$$

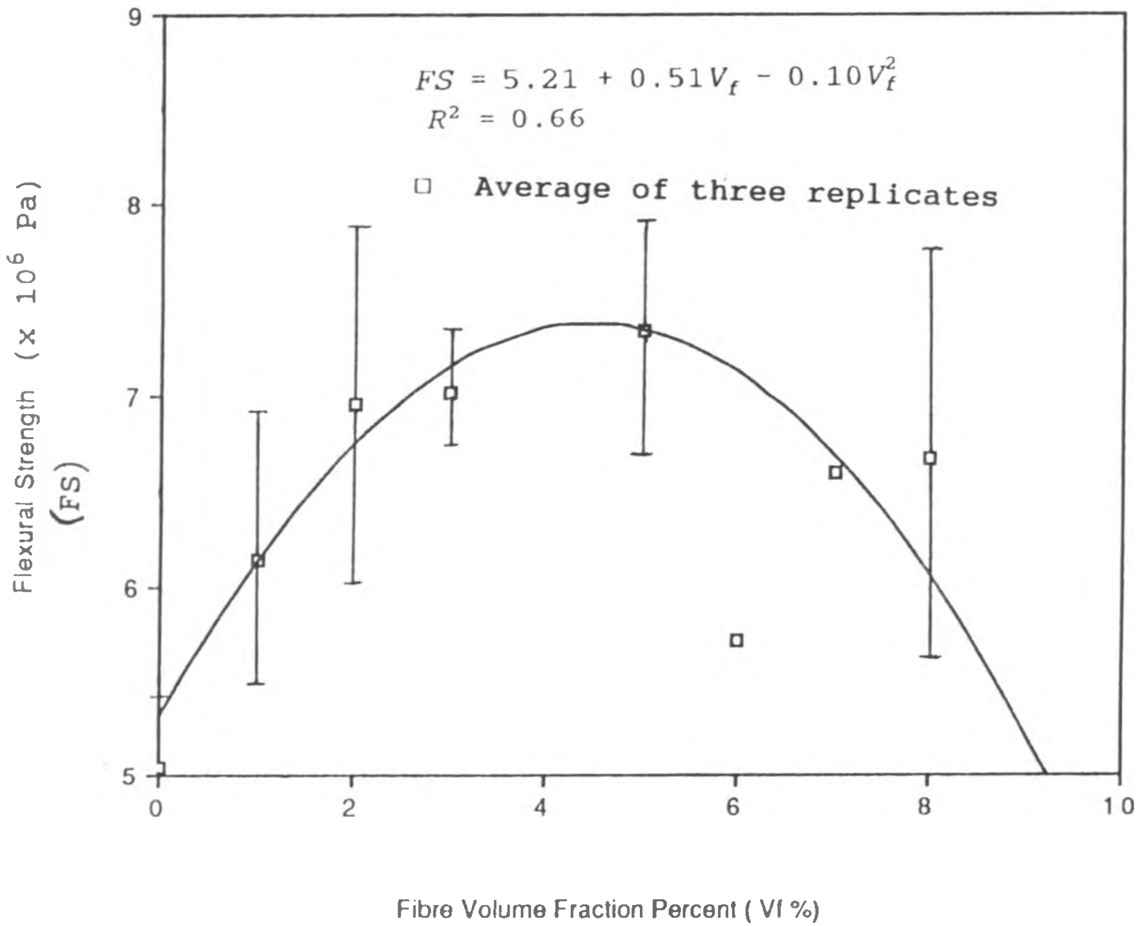


Figure 4.2 : Variation of maximum Flexural strengths with reinforcement fibre volume fraction for long parallel fibre-concrete composites.

The calculated strength at 0% V_f was 5.20 x 10^6 Pa and at 4.8% V_f was 7.60 x 10^6 Pa. An increment in strength of about 46% was observed. After 4.8% there was decrease in strength with increase in V_f . After 4.8% again it was observed that, there was a big scatter in the results and hence the low value of R^2. Multiple fracture was also observed to take place for these type of experiments.

The increment in strength possibly could be attributed to the fact that the fibre length used was greater than the critical fibre length. According to Kelly (1965), when the fibre length is the same or more than the critical fibre length, complete stress transfer takes place between the fibre and the matrix. For fibres shorter than the critical fibre length, failure of the composite is by pull-out and the full-strength of the fibre is not realized.

The decrease in strength and the big scatter of results observed after 4.8% V_f could be attributed possibly to the same reasons as given for Section 4.1, mainly poor compaction at high fibre contents and high water absorption capacity of the fibres.

It was also observed that the composites continued to carry more load after the first crack.

4.3 Tensile strength test results.

Figure 4.3 shows the regression curve for the variation of Tensile strength (TS) with fibre volume fraction (V_F) for chopped fibre-concrete composites. The regression equation was obtained as:

$$TS = 1.46 - 0.069V_f - 0.017V_f^2 \quad , \quad R^2 = 0.84 \quad ...(4.3)$$

The calculated strength at 0% V_f was 1.43×10^6 Pa. A progressive decrease in strength with increase in percent V_f was observed. The samples were also observed to fail in a single mode of failure with the fibres pulling out of the matrix. This could possibly be attributed to the same reasons as given in section 4.1 for Figure 4.1. These are mainly: fibre length, poor compaction, balling-up of fibres and the high water absorption capacity of the fibres.

Figure 4.4. shows the regression curve for the variation of Tensile strength (TS) with fibre volume fraction (V_f) for long parallel fibre concrete composites. The regression equation was obtained as:

$$TS = 1.47 + 0.14V_f - 0.012V_f^2 \quad , \quad R^2 = 0.51 \quad ...(4.4)$$

The calculated strength value at 0% V_f was 1.43×10^6 Pa and at 6% V_f was 1.83×10^6 Pa an increment of about 28%.

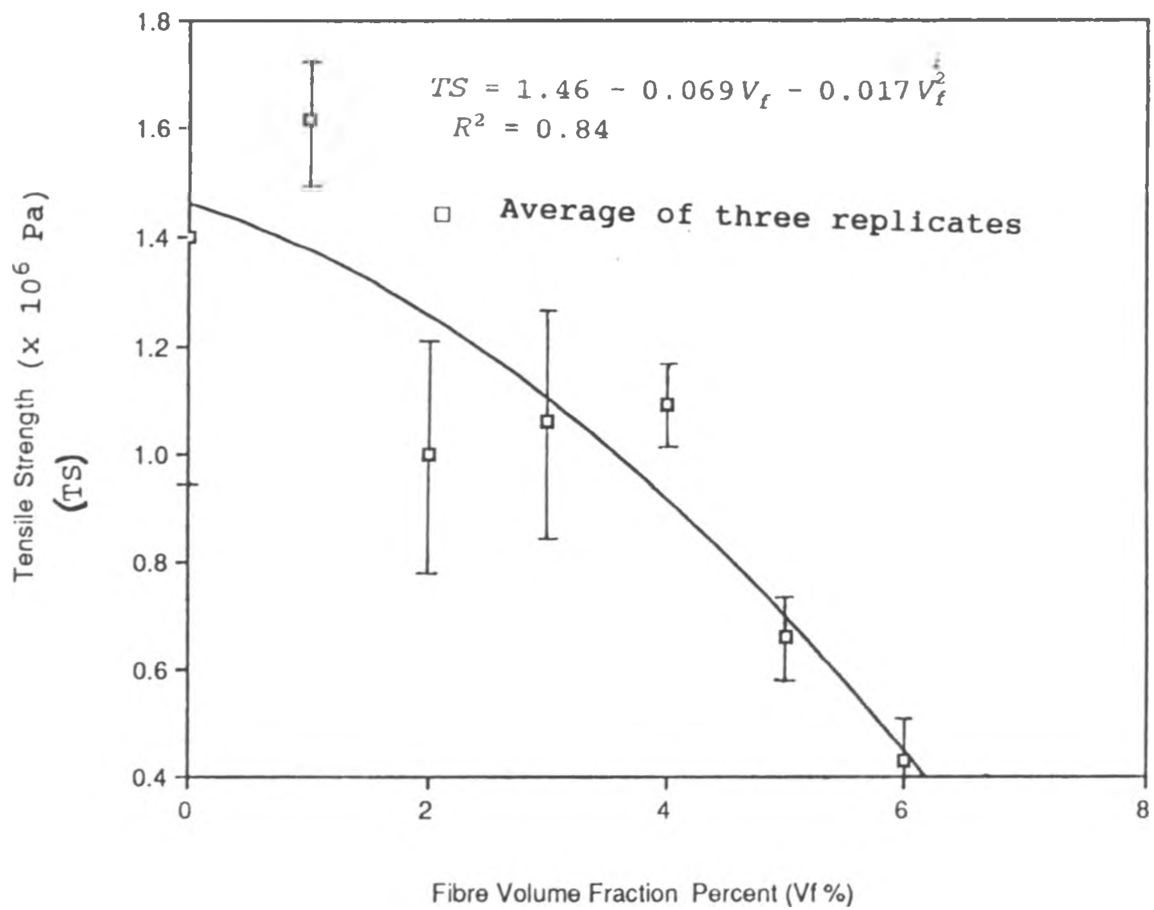


Figure 4.3 : Variation of Tensile strength with fibre volume fraction for chopped fibre-concrete composites.

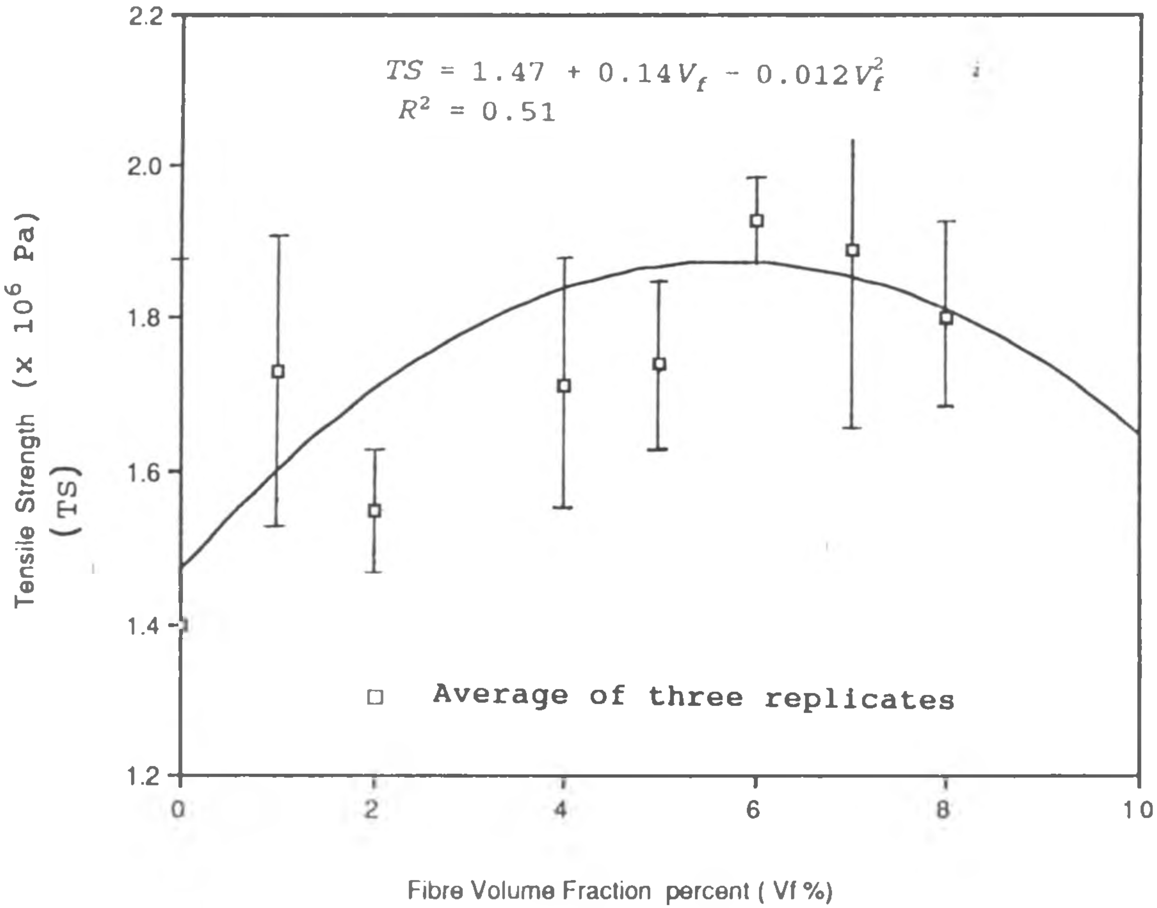


Figure 4.4 : Variation of maximum Tensile strengths with fibre volume fraction for long parallel fibre-concrete composites.

Multiple cracking was observed with the samples continuing to carry more weight after first crack. The increment in strength up to 6% V_f could possibly be attributed to the same reasons as in section 4.1 for Figure 4.2. The unstable curve observed could be attributed to the problems of poor compaction and high water absorption at these high fibre contents.

In comparison, it was observed that there was better percent increase in strength for Flexural strength samples reinforced with parallel fibres (Figure 4.2) than for Tensile strength samples reinforced the same way (Figure 4.4).

In comparison with results reported by other researchers earlier (see Table 4.10), the maximum value obtained in the study for parallel fibre reinforced samples tested in flexure, compares closely to that reported by Kirima and Mutuli (1990) for sisal mortar composite reinforced the same way of 9.3 x 10^6 Pa. It also compares closely to the value reported by West et al (1980) for light weight glass cement composite of 12 x 10^6 Pa.

In tensile strength, the results presented in this study for parallel fibre reinforced concrete compare closely to those presented by Kirima and Mutuli (1990) and West et al (1980) of 3.75 x 10^6 Pa and 4.5 x 10^6 respectively (see Table 4.10).

4.4 Toughness of Samples tested in flexure

Figure 4.5 shows the regression curve for the variation of Toughness (energy absorbed during loading, TG) with fibre volume fraction (V_f) for chopped fibre-concrete composites in flexure. The regression equation was obtained as:

$$TG = 8.26 + 5.94V_f - 0.49V_f^2 \quad , \quad R^2 = 0.81 \qquad ...(4.5)$$

The calculated value of Toughness at 0% V_f was found to be 8.4 Nm and at 6%, 26Nm, an increment of about 200%.

Figure. 4.6 shows the regression curve for the variation of Toughness (TG) with fibre volume fraction (V_f) for parallel fibre-concrete composites in flexure. The regression equation was obtained as:

$$TG = -37.15 + 133.42V_f - 12.1V_f^2 \quad , \quad R^2 = 0.83 \qquad ...(4.6)$$

The calculated value of Toughness at 0% V_f was 8.4Nm at 5% V_f was 340Nm, an increment of about 39 times was observed (3900%). After 5% V_f, the toughness was observed to decrease with increase in V_f.

The high percent increase in toughness could possibly be attributed to the relatively good bonding that goes with long parallel fibres as discussed in Section 4.1..

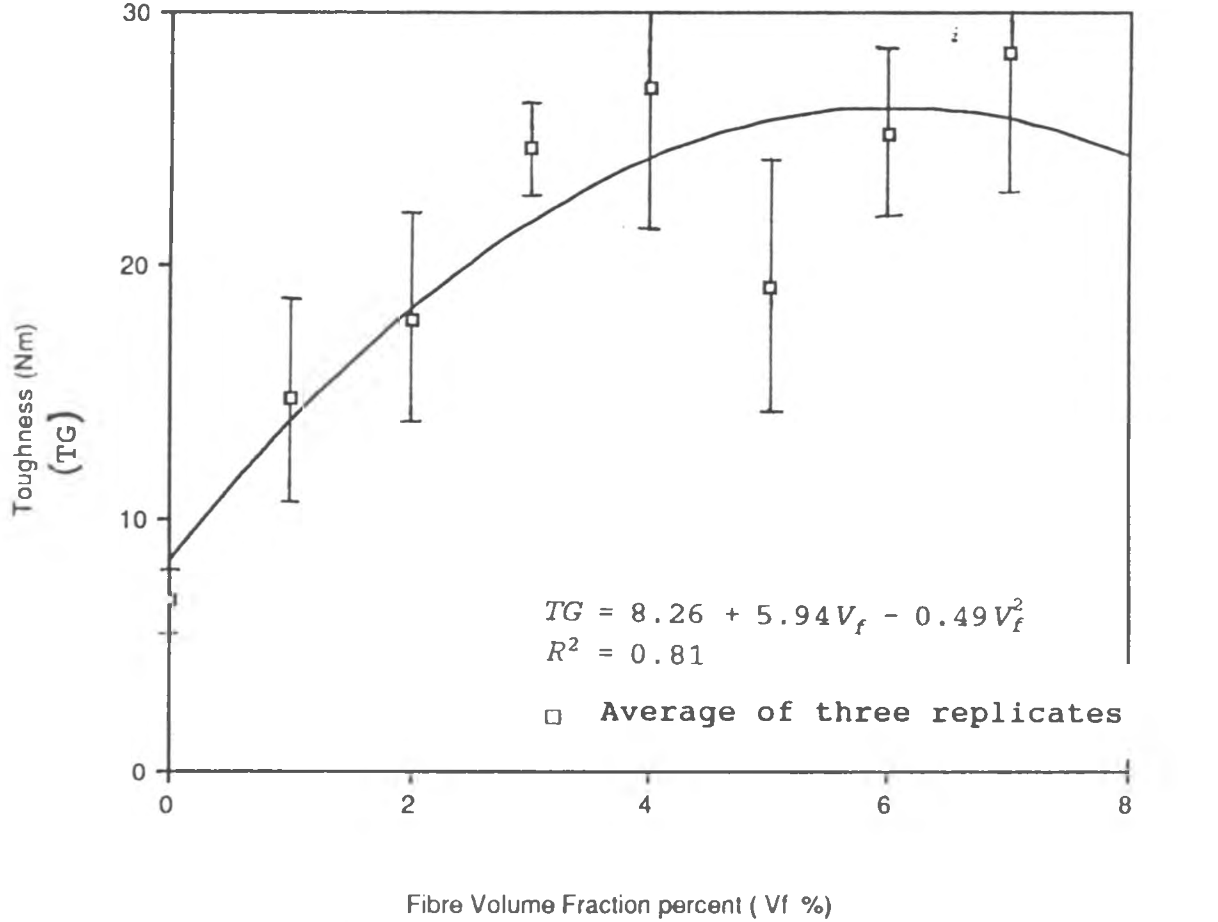


Figure 4.5 : Variation of Toughness with fibre volume fraction for chopped fibre-concrete composites in flexure.

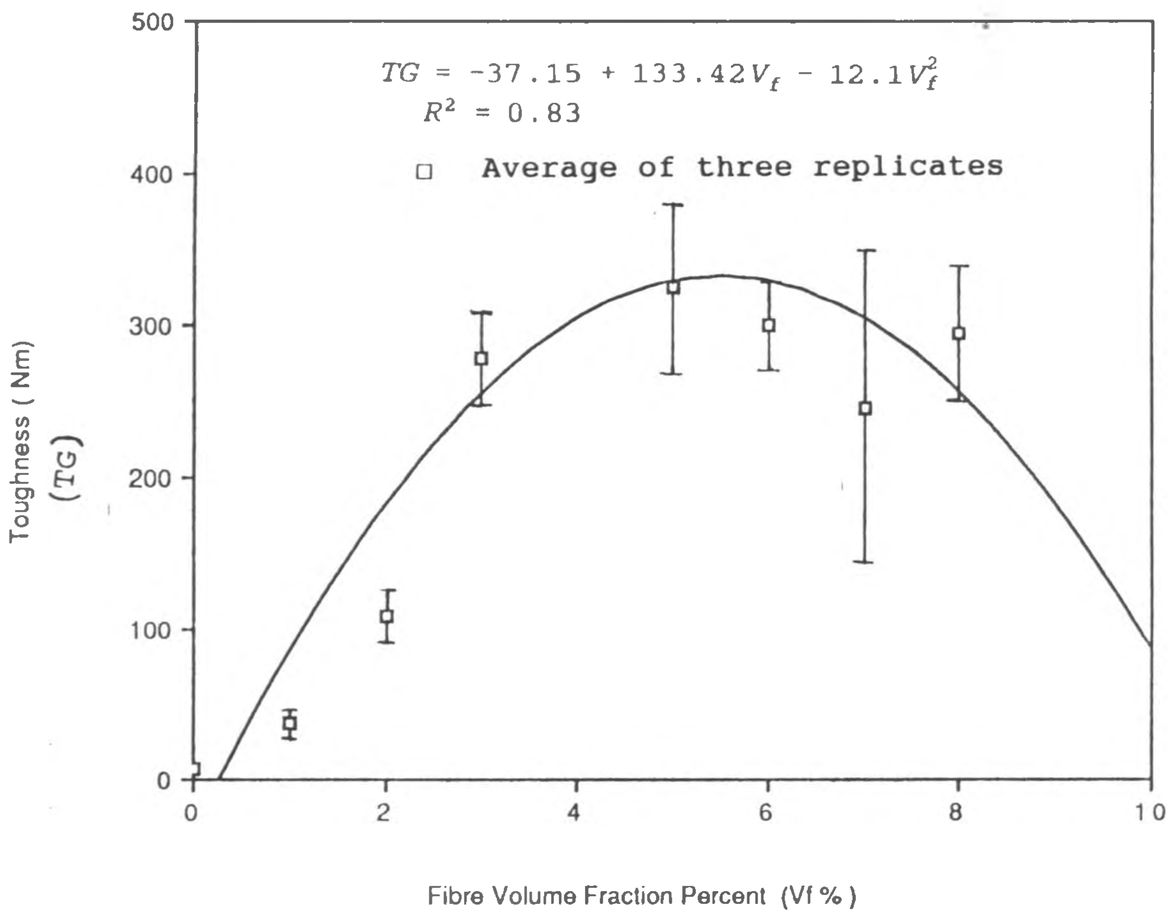


Figure 4.6 : Variation of Toughness with fibre volume fraction for parallel fibre-concrete composites in flexure.

The specimen could still hold more weight long after first crack and multiple cracking failure mode was observed. This implied better energy absorption and better impact resistant in bending.

4.5 Toughness of Samples tested in Tension

Figure 4.7 shows the regression curve for the variation of Toughness (TG) with fibre volume fraction (V_f) for chopped fibre-concrete composites tested in tension. The regression equation was obtained as:

$$TG = 7.20 + 0.26V_f - 0.19V_f^2 \quad , \quad R^2 = 0.74 \qquad ...(4.7)$$

The calculated Toughness at 0% V_f was 7.2Nm. A progressive decrease in toughness with increase in V_f was observed. This poor ability to absorb energy seen for this type of reinforcement can be explained by the same reasons as in section 4.3 for the same types of reinforcement, that is, fibre length and the high water absorption capacity of the fibres.

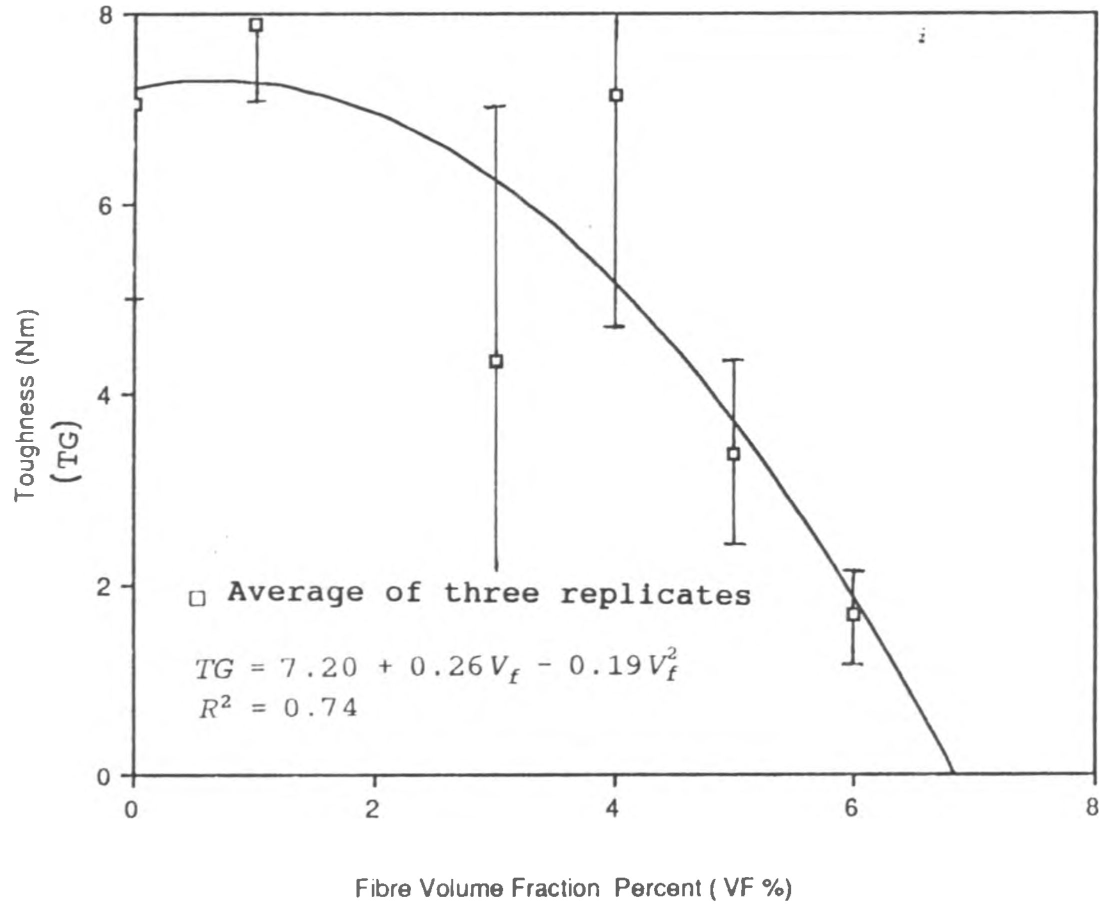


Figure 4.7 : Variation of Toughness with fibre volume fraction for chopped fibre-concrete composites in tension.

Figure 4.8. shows the regression curve for the variation of Toughness (TG) with fibre volume fraction (V_f) for parallel fibre-concrete composites tested in tension. The regression equation was obtained as:

$$TG = 4.30 + 34.98V_f - 2.79V_f^2 \quad , \quad R^2 = 0.81 \qquad ...(4.8)$$

The calculated value of Toughness at 0% V_f was 7Nm and at 6% V_f was 117Nm. An increment of about 16 times (1600%) was observed. This could possibly be explained by the same reasons as in section 4.3 for Figure 4.4 . The main reason being the better bonding associated with parallel fibre reinforcement.

This tremendous increase in toughness and poor increase in strength agreed with what was observed by Swamy ((1974) and Zonsveld (1975), that low modulus fibres do not confer a satisfactory increase in both tensile strength and flexural strength upon hardened concrete but remarkably improves the toughness and the impact resistance.

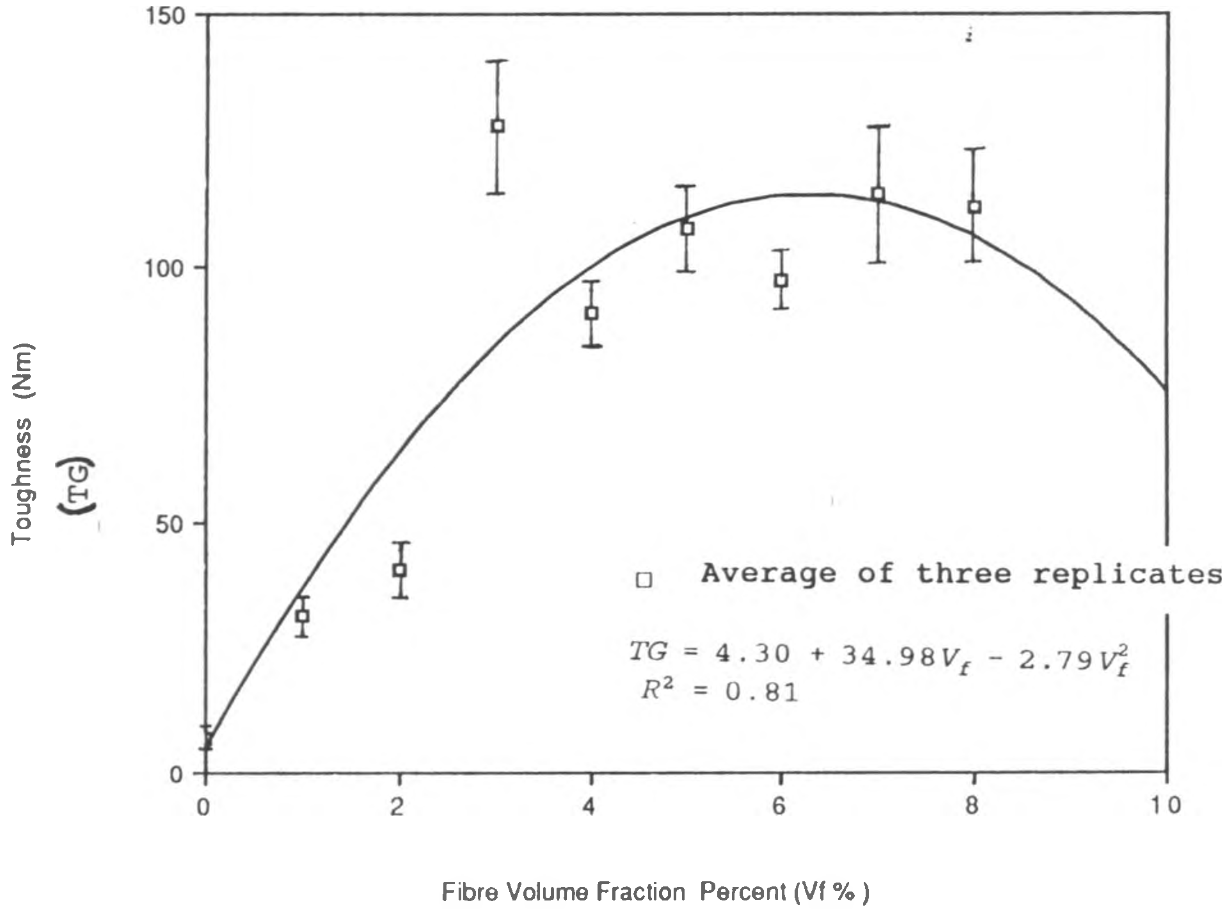


Figure 4.8 : Variation of Toughness with fibre volume fraction for parallel fibre-concrete composites in tension.

The specimens reinforced with parallel fibres tested in both tension and flexure exhibited multiple cracking mode of failure. In tension, the cracks occurred in the direction normal to the applied load. For the specimens tested in flexure, the first crack occurred near the bottom middle of the specimen in the direction parallel to the applied load. This is because , this is the point subjected to the highest indirect tensile stress. On further loading, more cracks appeared on both side of the first one. In both this two types of tests, the failure was accompanied by fibre pulling out of the matrix. The composites were able to withstand more loading long after the first crack.

The specimens reinforced with chopped fibres tested in both tension and flexure exhibited a single crack mode of failure accompanied by fibre pull-out. In the tensile tests, the cracks occurred in the direction normal to the applied load. In the flexural tests, the cracks occurred in the direction parallel to the applied load.

These two modes of failure agreed well with what was reported earlier by other researchers.

The mode of fracture in a fibre reinforced composite is influenced by the relative magnitudes of failure strengths and strains of matrix and fibre. Single modes of fracture are normally seen in matrices that have similar magnitudes of strains as that of the reinforcing fibre or where the failure strain of fibre is less than that of matrix, the onset of fibre failure leads to composite failure as the matrix cannot withstand the load alone (Nicholls, 1976).

For chopped fibre reinforced composites, Kelly (1965) introduced the concept of the critical fibre length on which complete stress transfer takes place between the fibre and the matrix (See section 2.1.7). For fibres shorter than the critical length, the composite exhibits the single crack mode of failure accompanied by fibre pull-out and the full strength of the fibre is not realized.

For brittle matrices reinforced with fibres of relatively greater breaking strains, provided that there are sufficient fibres to support the load after the matrix has failed, the composite fails exhibiting multiple cracking mode of failure, with the composite behaving in a Pseudo-ductile fashion. Multiple cracking will continue until final fracture takes place (Nicholls, 1976).

Bessell and Mutuli (1982) reported that, for brittle matrix composites reinforced with ductile fibres, the tensile fracture will take place by multiple cracking of the matrix in the direction normal to the applied load. The ductile fibres will initially bridge the cracks by taking up all the load and will eventually fail themselves.

4.6 Interfacial Bond Strength For Concrete Reinforced with Randomly oriented fibres

Swamy and Mangat (1976) presented a method for determination of the interfacial bond strength for concrete reinforced with short discrete fibres randomly oriented and uniformly distributed throughout the matrix for fibres free from balling and curling (see section 2.4.6).

The results of this study agreed partially with what they reported. A plot of σ_{fc} $/V_f(L/d)$ versus σ_m $(1 - V_f)/V_f$ (L/d) produced a straight line but gave a negative value for the interfacial bond strength (see Figure 4.9). The interfacial bond strength (τ) for chopped fibre-concrete was found to be -4.3 x 10^5 Pa (-0.43 N/mm^2) and the constant A as 0.814. The equation for the flexural strength (σ_{fc}) of the composite was evaluated as:

$$\sigma_{fc} = 0.814\,\sigma_m\,(1-V_f) - 0.353V_f\,(\frac{L}{d}) \qquad ...(4.9)$$

The negative value of interfacial bond strength obtained showed that this method cannot be applied in case of sisal fibre-concrete composites. This is because, it is not practical to have a negative bond strength. This could possibly be due to the following reasons:

(a) The method used in this study was designed for fibres that are free from balling-up and curling. In this study, there was a lot of fibre balling and curling and this could have caused this poor results.

(b) Because of the balling-up and curling of the fibres, it was not possible to obtain a uniform distribution of the fibres in the matrix. In order to obtain a reliable value for the bond strength, the fibre distribution in the matrix should be uniform.

(c) Sisal fibres have a high water absorption capacity unlike steel fibres. The sisal fibres absorb a good amount of the water added for mixing and this reduces the water-cement ratio which is a major factor affecting the composite strength.

(d) Sisal fibres are less stiff, have a larger variation in cross-sectional area and an irregular cross-section as compared to steel fibres.

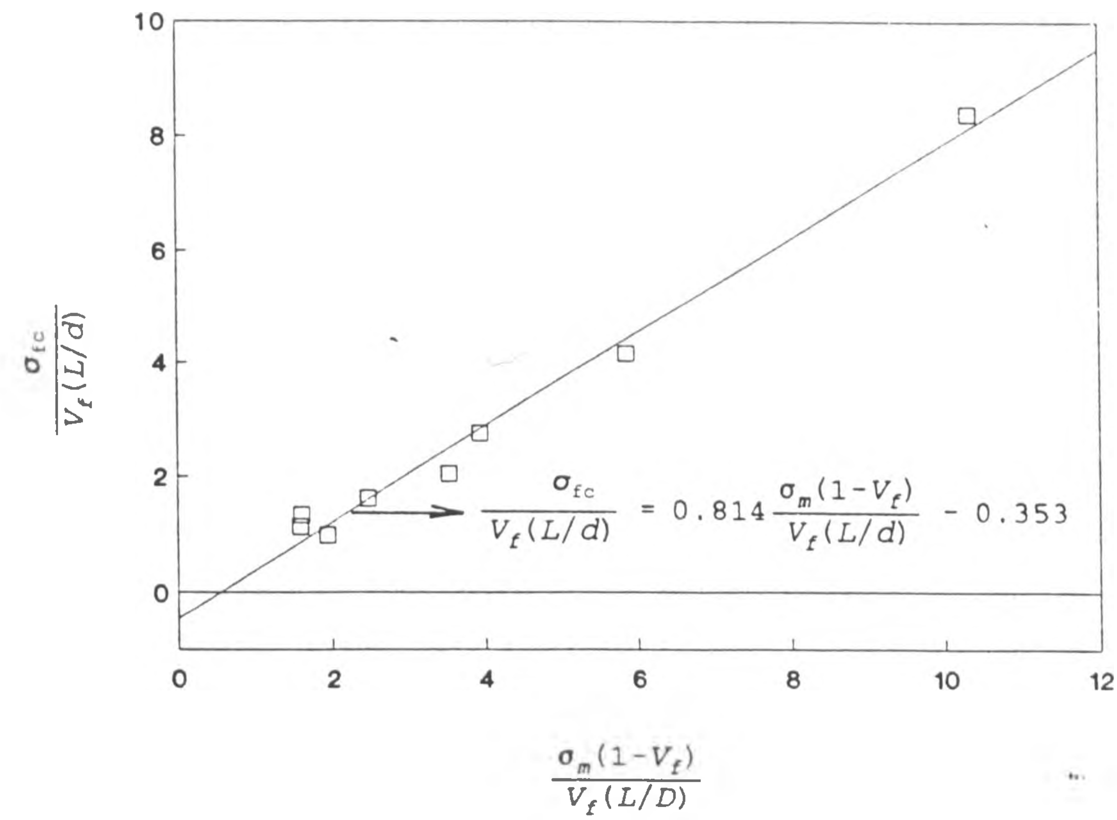


Figure 4.9 : Graph of σ_{fc} /{V_f (L/d)} versus σ_m (1-V_f)/{V_f (L/d)} for chopped fibre-concrete composites in flexure.

4.7 Interfacial Bond Strength For Concrete Reinforced With Parallel Fibres

The Interfacial Bond Strength for parallel fibre-concrete was obtained by use of Aveston's equation (see section 2.4.6.). A plot of the crack spacing (x) versus $(1-V_f)/V_f$ produced a straight line passing almost through the origin with a gradient of 2.5 (see Figure 4.10). The interfacial bond strength (τ) was found to be 0.028 N/mm^2 (2.8×10^4 Pa).

In comparison with other values of bond strength reported earlier for different matrices (see Table 4.10), the value obtained in this study compared by about 56% to that obtained by Baggot and Gadhi (1981) for polypropylene fibre reinforced concrete of 5.0×10^4 Pa. In comparison with the other values from Table 4.10, of other matrices, the value obtained here was low. This could possibly be attributed to the following reasons:

(a) Swamy and Mangat (1976) reported that, the change from cement paste to concrete is accompanied by a progressive reduction in bond strength. The matrix used in this study was concrete of 1:2:2.5 mix while all the other composites used for comparison had cement paste as the matrix. Therefore this poor comparison is expected, that is, the bond strength for the composites using the concrete matrix is expected to be lower than for the composites using cement paste matrix. This is because more voids exist in concrete matrix than in cement matrix.

(b) Sisal fibres have a high water absorption capacity and therefore this would affect the water-cement ratio which would result to poor bonding. This would happen because according Swamy and Mangat (1976), the matrix strength contributes to the interfacial bond strength and when the fibres absorb the water used for mixing, this lowers the water-cement ratio and hence lowering the matrix strength.

(c) The method used in this study was presented by Aveston et al (1971) and was used for steel fibres. Due to the stiffness, surface characteristics, and the cross sectional area of the sisal fibres, it was hard to obtain correctly parallel aligned fibres as it is required by the method. Therefore the value obtained was an approximation.

(d) At high fibre contents, it was not possible for the fibres to be well coated individually by the matrix. This resulted to some fibres not being bonded to the matrix.

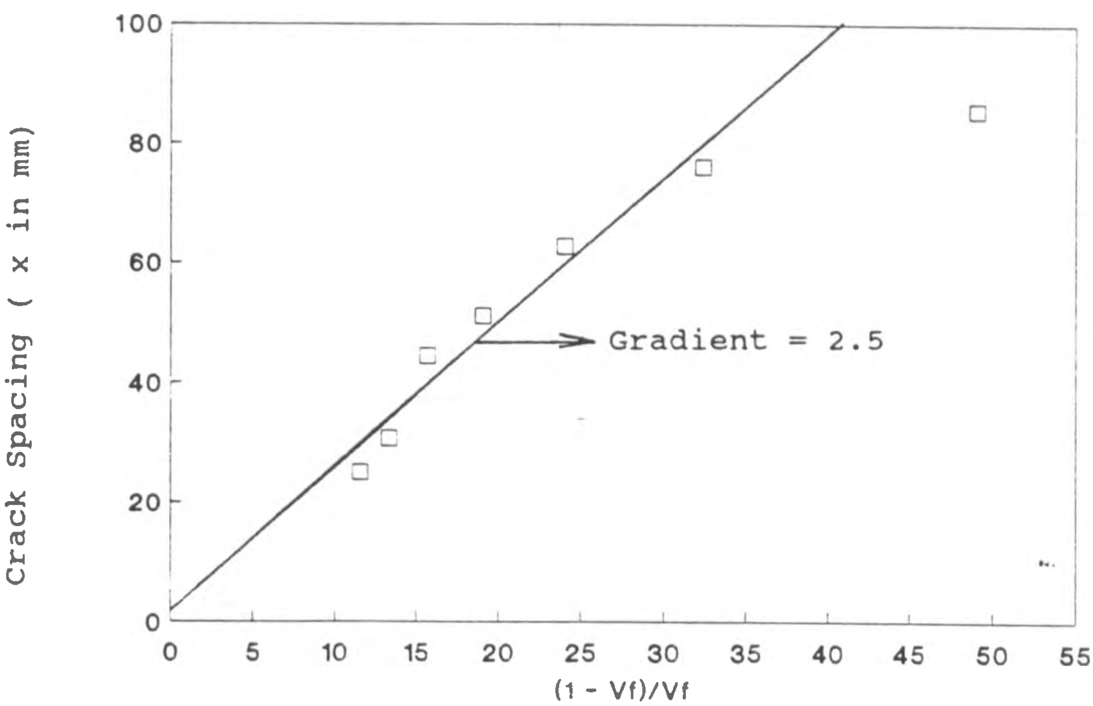


Figure 4.10. Crack spacing (x in mm) versus $(1-V_f)/V_f$ (where V_f is the fibre volume fraction).

Table 4.2. Variation of Flexural strength with reinforcement fibre volume fraction for chopped fibre-concrete composites.

Vf (%)	Flexural strength ($x10^6$ Pa) 1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	5.40	5.00	4.73	5.04	0.34
1	4.86	5.49	5.22	5.19	0.32
2	4.55	5.54	4.23	4.77	0.68
3	4.27	4.32	4.23	4.27	0.05
4	4.02	3.89	4.59	4.17	0.37
5	3.76	3.15	3.11	3.34	0.36
6	3.06	3.96	2.54	3.19	0.72
7	2.70	2.84	2.48	2.67	0.18

rep. = replication

Table 4.3. Variation of maximum flexural strength with fibre volume fraction for long and parallel fibre-concrete composites.

V_f (%)	Maximum Flexural strength ($x 10^6$ Pa) 1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	5.40	5.00	4.73	5.04	0.34
1	6.44	5.22	6.75	6.14	0.81
2	8.10	6.48	6.34	6.97	0.98
3	6.80	7.24	*	7.02	0.31
4	9.54	8.64	7.02	8.40	1.28
5	6.70	7.20	8.10	7.33	0.71
6	8.21	4.72	4.23	5.72	2.17
7	7.96	7.78	4.05	6.60	2.21
8	7.09	7.69	5.27	6.68	1.26

* = missing value
rep. = replication

Table 4.4. Variation of Tensile strength with fibre volume fraction for chopped fibre-concrete composites.

V_f (%)	Tensile strength (x 10^6 Pa) 1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	0.90	1.83	1.46	1.40	0.47
1	1.50	1.73	*	1.62	0.16
2	1.12	1.16	0.73	1.00	0.24
3	0.82	1.12	1.25	1.06	0.22
4	0.97	1.13	1.18	1.09	0.11
5	0.60	0.80	0.58	0.66	0.12
6	0.53	0.42	0.34	0.43	0.10

* = missing value
rep. = replication

Table 4.5. Variation of maximum Tensile strength with fibre volume fraction for long and parallel fibre-concrete composites.

V_f (%)	Max. Tensile strength (x10^6 Pa) 1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	0.90	1.83	1.46	1.40	0.47
1	1.66	1.95	1.59	1.73	0.19
2	1.48	1.59	1.59	1.55	0.06
3	2.03	1.99	2.11	2.04	0.06
4	1.85	1.55	1.73	1.71	0.15
5	1.83	1.78	1.62	1.74	0.11
6	1.92	1.88	2.00	1.93	0.06
7	2.15	1.66	1.85	1.89	0.25
8	1.88	1.98	1.71	1.86	0.14

rep. = replication

Table 4.6. Variation of Toughness with fibre volume fraction for chopped fibre-concrete composites in flexure.

V_f (%)	Area Under Load-defl. curves (Nm)				
	1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	7.04	7.30	6.00	6.78	0.69
1	14.09	10.96	19.04	14.70	4.07
2	13.57	21.65	18.39	17.87	4.07
3	23.09	26.35	24.26	24.57	1.65
4	26.22	21.39	33.26	26.96	5.97
5	20.35	23.74	13.17	19.09	5.40
6	27.26	21.91	26.35	25.17	2.86
7	31.96	30.91	22.17	28.35	5.37

rep. = replication

Table 4.7. Variation of Toughness with fibre volume fraction for long and parallel fibre-concrete composites in flexure.

V_f (%)	Area Under Load -defl. curves (Nm)				
	1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	7.04	7.30	6.00	6.78	0.69
1	32.22	43.30	39.91	38.48	5.68
2	127.04	116.74	85.70	109.83	21.52
3	304.43	250.43	*	277.43	38.18
4	406.96	420.00	384.52	403.83	17.95
5	277.04	309.39	388.70	325.04	57.45
6	339.13	200.35	180.52	240.00	86.42
7	323.48	119.49	292.17	245.05	109.86
8	306.78	334.96	241.57	294.44	47.90

* = missing value
rep. = replication

Table 4.8. Variation of Toughness with fibre volume fraction for chopped fibre-concrete composites in tension.

Vf (%)	Area Under Load-defl. curves (Nm)				
	1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	9.39	5.74	6.00	7.04	2.04
1	13.30	4.96	5.40	7.89	0.31
2	4.17	1.83	*	3.00	1.65
3	2.09	3.65	7.30	4.35	2.67
4	3.44	7.20	10.82	7.15	2.66
5	2.19	3.55	4.38	3.37	1.11
6	2.09	1.98	1.03	1.70	0.53

* = missing value
rep. = replication

Table 4.9. Variation of Toughness with fibre volume fraction for long and parallel fibre-concrete composites in tension.

Vf (%)	Area Under Load-defl. curves (Nm)				
	1st. rep.	2nd. rep.	3rd. rep.	Mean	Standard deviation
0	9.39	5.74	6.00	7.04	2.04
1	29.48	37.30	27.91	31.56	5.03
2	46.17	34.17	42.00	40.78	6.09
3	138.52	132.78	111.91	127.74	14.00
4	97.30	94.17	81.65	91.04	8.28
5	127.30	100.96	94.96	107.74	17.20
6	107.22	95.48	88.96	97.22	9.25
7	128.09	103.57	112.43	114.70	12.42
8	111.91	124.17	99.65	111.91	12.26

rep. = replication

Table 4.10. Some properties of Cement base composites reinforced with different types of fibres.

Composite	Bond strength ($\times 10^6$ Pa)	Tensile strength ($\times 10^6$ Pa)	Flexural strength ($\times 10^6$ Pa)
Polypropylene fibre reinforced cement (Baggot and Gadhi, 1981)	0.05		
Sisal fibre cement composite (Bessell and Mutuli, 1982)	0.60		
Steel fibre cement composite (Swamy and Mangat, 1976)	4.15		
Polyethylene-cement (Walton et al, 1984)		37.2	46
Carbon-cement (Waller, 1973)			295
Air-cured wood pulp fibre-cement mortars (coults, 1987)			20
Light weight glass fibre reinforcement (West et al, 1980)		4.5	12
Glass fibre-cement (Marsh et al, 1973)			16.2
Sisal fibre-Mortar (Kirima and Mutuli, 1990)		3.75 (parallel) 2.8 (chopped)	9.3(parallel) 4.7(chopped)

5.0 CONCLUSIONS

5.1 Effect of Reinforcement on Flexural and Tensile Strengths

Within the range of this study, small increases in both Flexural and Tensile strength were observed for only one type of reinforcement, Parallel fibre reinforcement. There was no increase in both Flexural and Tensile Strength for chopped fibre randomly oriented reinforcement.

The Flexural and Tensile Strength were found to increase with V_f for Parallel fibre reinforcement up to a maximum value at a given V_f, and then a decrease with increase of V_f. An increment of about 46% for the Flexural Strength was observed at 4.8% fibre volume fraction while for Tensile strength was 28% at 6% fibre volume fraction. The Flexural Strength and Tensile Strength were found to decrease with V_f for chopped fibre reinforcement.

It can be concluded at this point that, sisal fibre reinforcement does not give a satisfactory improvement on the strength of concrete. This is because, although some strength increment was observed for parallel fibre form of reinforcement this form of reinforcement is not very practical. This is because, it is not possible to mechanize this form of reinforcement and the fibres have to be arranged by hand and due to the nature of the sisal fibre, it is very time consuming (no like steel fibres).

Chopped fibres and randomly reinforced composites are easier to make and therefore more research on different lengths of fibre may produce better results.

5.2 Effect of fibre Reinforcement on Toughness

As reported in Sections 4.4 and 4.5, toughness was seen to increase for both forms of reinforcement. Flexural toughness was seen to increase by about 200% for chopped fibre reinforcement at 6% V_f and by about 3900% for parallel fibre reinforcement at 5% V_f. In Tension, the toughness increased by about 1600% for only parallel fibre reinforcement at 6% V_f.

It can therefore be concluded that sisal fibre reinforcement of concrete improves the toughness (energy absorption) considerably but no improvement on strength. This agrees with what was reported by Swamy (1974) and Zonsveld (1975), that high strength, high modulus fibres impart strength and stiffness to the composites, whereas low modulus, high elongation fibres would result to large energy absorption characteristics and impart toughness and resistance to impact and explosive loading.

According to Keer (1984), an improvement in toughness also results to better impact resistant products. Therefore sisal fibre Reinforced concrete products should be applied in situations where impact loading occur. The toughness in all cases was observed to increase with fibre volume fraction and the increase was more on parallel fibre reinforced sample.

5.3 Fibre - Matrix Interfacial Bond

A value of -0.43 N/mm^2 was found for the interfacial bond strength for chopped fibres randomly reinforced. Since it is not possible to have a negative bond strength, it was concluded that, the method by Swamy and Mangat (1976) which was applied in this study is not suitable for the calculation of the bond strength for sisal fibre concrete composites.

The method by Aveston (see section 2.1.6) produced a value of the interfacial bond strength for concrete reinforced with parallel sisal fibres of 0.028 N/mm^2. This was taken as the true approximate value taking into consideration other factors as discussed in section 4.7. Therefore it was concluded that, Aveston's method can be used for the determination of the interfacial bond strength for sisal fibre-concrete composites.

6.0 RECOMMENDATIONS FOR FUTURE WORK

For a better understanding of the sisal fibre-concrete composite, which may lead to subsequent practical utilization of the composite the following areas should be investigated further:

(1) It is not possible at this point to conclude that, chopped fibres form of reinforcement does not improve the strength of concrete as depicted in this research. This is because only one particular length was used. There is therefore a need to establish whether other lengths will improve the strength of concrete.

(2) For the chopped fibres reinforcement of concrete in this study, the conventional power driven concrete mixer was used. This resulted to a lot of fibre balling-up and curling. Therefore, there is a need for a special concrete mixer which will be able to mix the fibres with the concrete without balling-up and curling of the fibres.

(3) In this study, due to time and financial limitations, it was not possible to study all the properties of sisal fibre reinforced concrete. There is therefore a need for more research on the following :

   (a) Impact behaviour of the composite

   (b) Fracture toughness and

   (c) Water absorption.

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8.0 **APPENDICES**

Appendix A: Tables

Table 8.1. The mechanical and physical properties of sisal fibres (Mutuli, 1979)

Property	Value	Standard deviation
Tensile strength* (MN/m^2)	347.0	110.0
Modulus of Elasticity* (N/m^2)	14.0	3.0
Elongation to failure* (%)	5.0	1.0
Tensile Strength** (N/m^2)	325.0	100.0
Modulus of Elasticity** (N/m^2)	7.0	2.5
Elongation to Failure** (%)	8.0	2.0
Specific gravity	0.7 ± 0.1	
Cross sectional area (mean, m^2)	5×10^{8}	
Cross sectional area (range, m^2)	$(2 - 10) \times 10^{-8}$	

* Normal atmospheric conditions, 25°c, 60% relative humidity.

** After soaking in water for 48 hours.

Table 8.2. Physical and Mechanical properties of some vegetable fibres (Aziz et al, 1984)

Fibre type	Tensile strength (N/mm^2)	Modulus of elas- -ticity (kN/mm^2)	Bulk density (kg/m^3)	Elong- -ation at break (%)	Water absor- -ption (%)
Sisal	280-568	13-26	700-800	3-5	60-70
Coconut	120-200	19-26	145-280	10-25	13-180
sugarcane bagasse	170-290	15-19	-	-	70-75
Jute	250-350	26-32	-	1.5-1.9	-
Flax	1000	100	-	1.8-2.2	-

Table 8.3. Sisal Production, Export and Local sales volumes in Kenya for the last ten years (Source Kenya Sisal Board, 1992)

YEARS	PRODUCTION (MTons)	EXPORT VOLUME (MTons)	LOCAL SALES (MTons)	TOTAL VOLUME SOLD (MTons)
1982	50028	40808	2357	43165
1983	49728	38486	6410	44896
1984	51438	39505	2728	42233
1985	44915	38435	6969	45404
1986	41507	31913	7190	39103
1987	37024	28493	9963	38456
1988	36972	30701	6017	36718
1989	37319	32223	7930	40153
1990	36917	30829	6792	37621
1991	39800	24436	4228	28664

Table 8.4. Variation of crack spacing (x) with fibre volume fraction (V_f) for parallel fibre reinforced samples in tension.

Spacing (mm)	Volume fraction (V_f)	$(1-V_f)/V_f$
93.33	0.01	99.00
85.67	0.02	49.00
76.00	0.03	32.33
62.67	0.04	24.00
51.00	0.05	19.00
44.33	0.06	15.67
30.67	0.07	13.29
25.00	0.08	11.50

Appendix B: Figures.

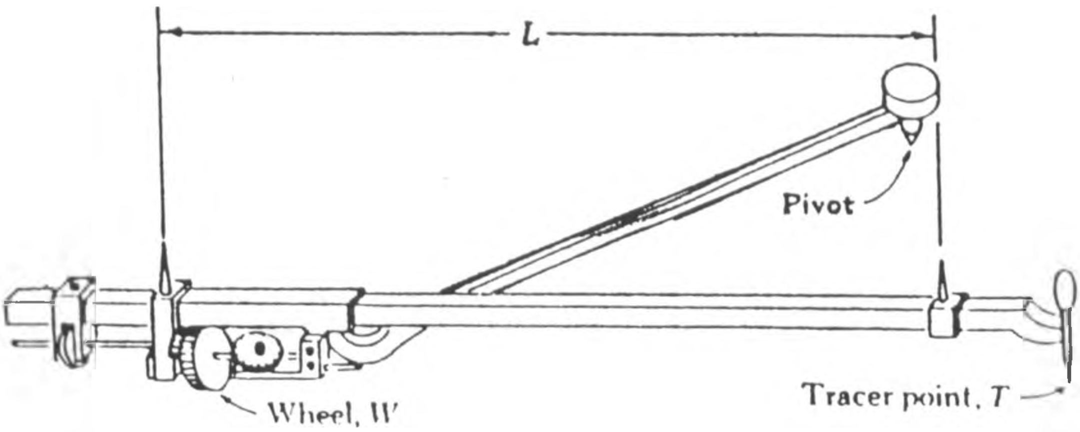


Figure 8.1: A planimeter for measuring area

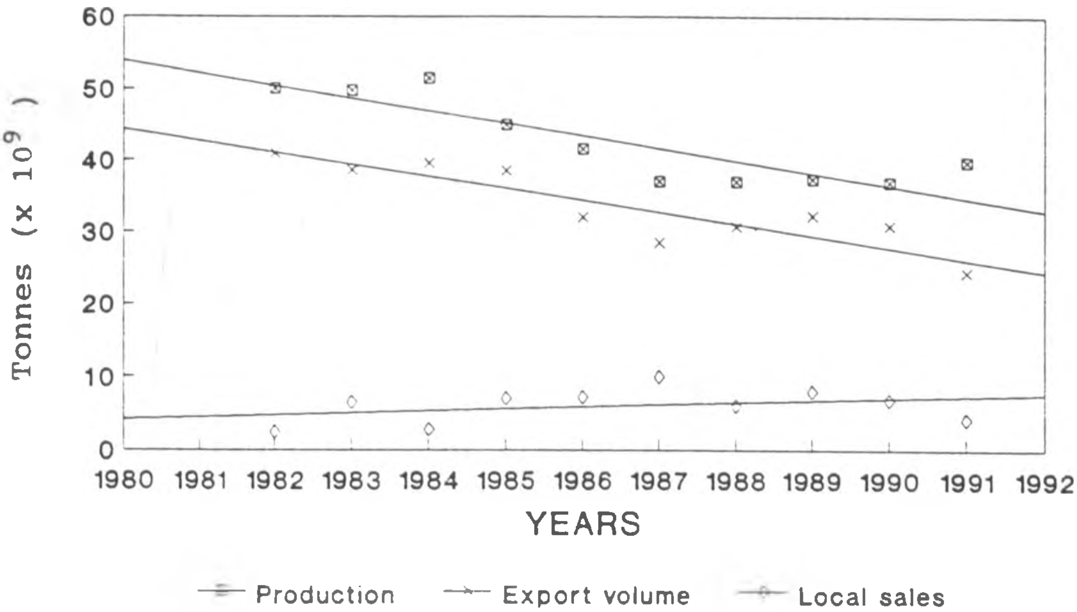


Figure 8.2: Sisal Production, Export volumes and Local sales Trends for the last ten years in kenya.

Appendix C: Typical load-extension curves.

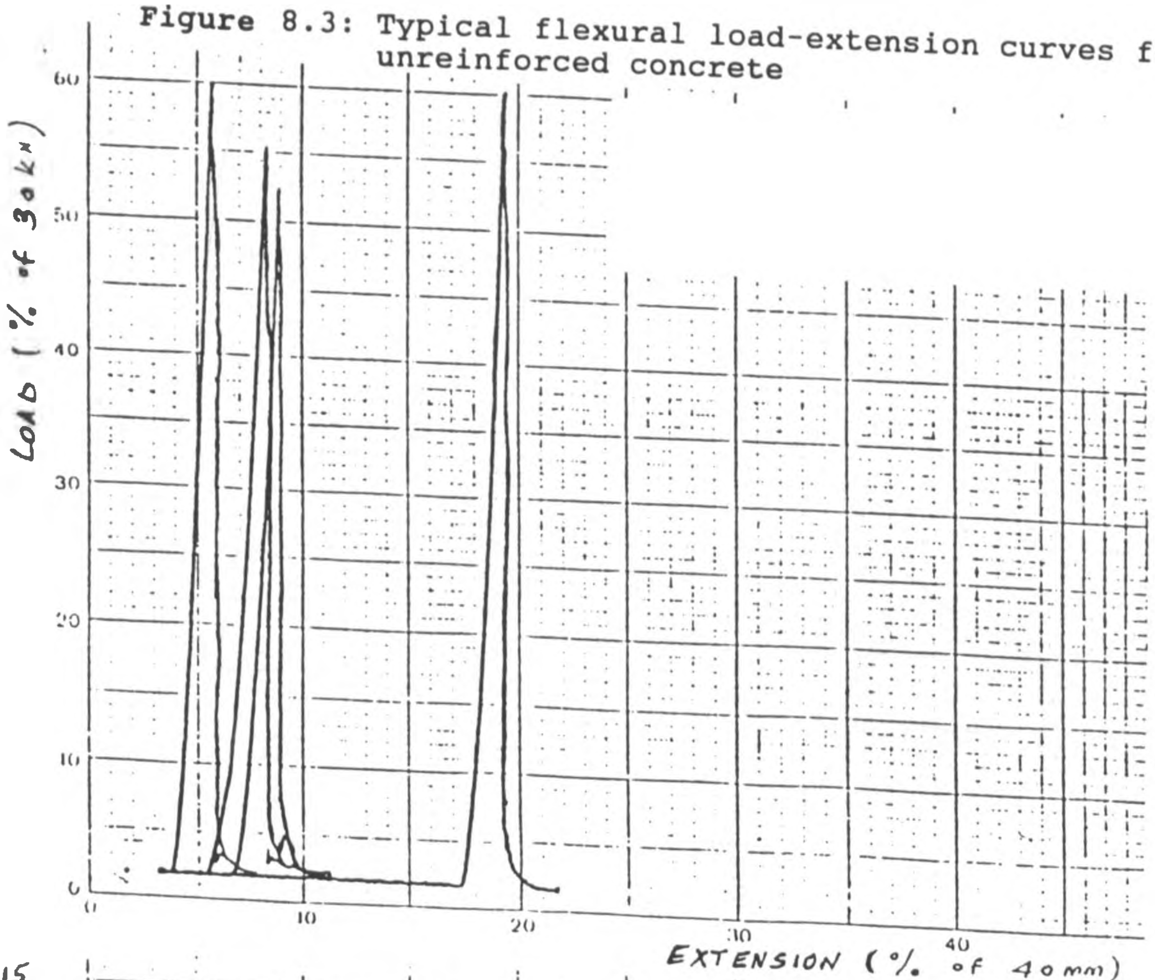


Figure 8.3: Typical flexural load-extension curves for unreinforced concrete

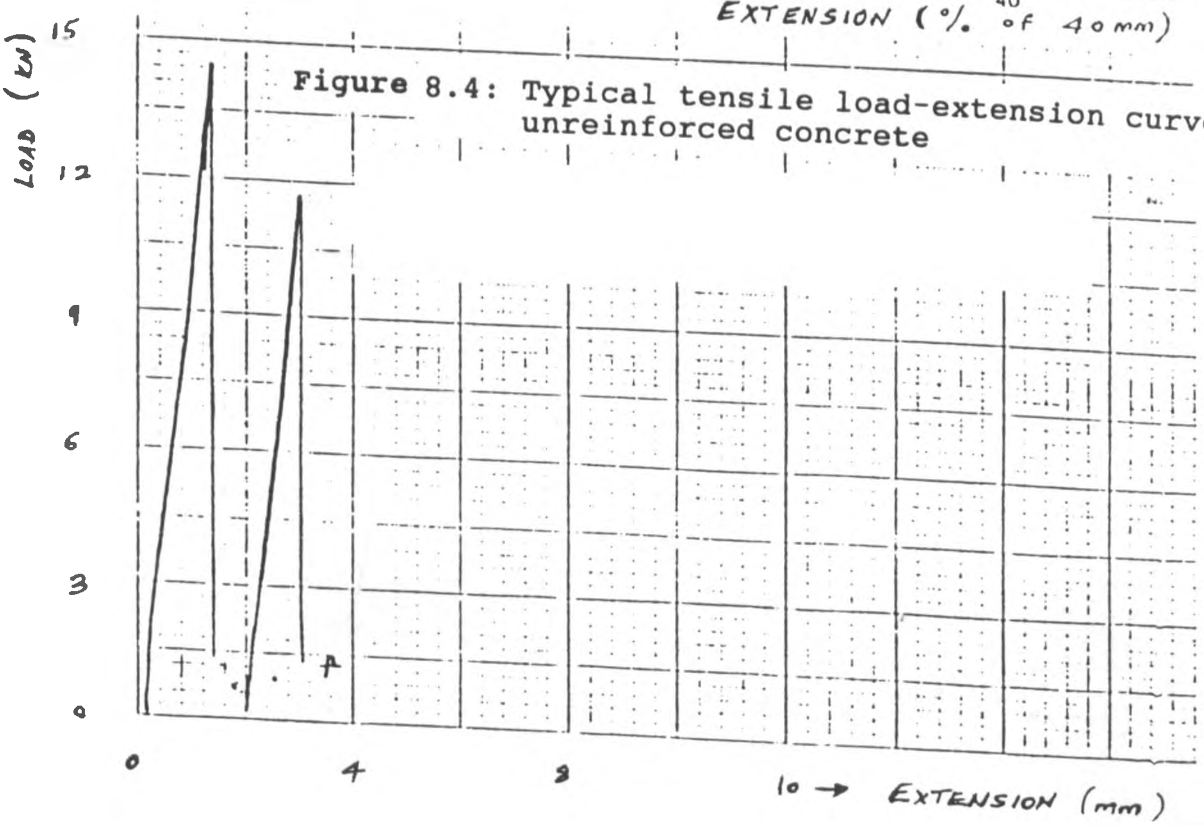


Figure 8.4: Typical tensile load-extension curves for unreinforced concrete

Figure 8.5: Typical flexural load-extension curves for concrete reinforced with chopped sisal fibres

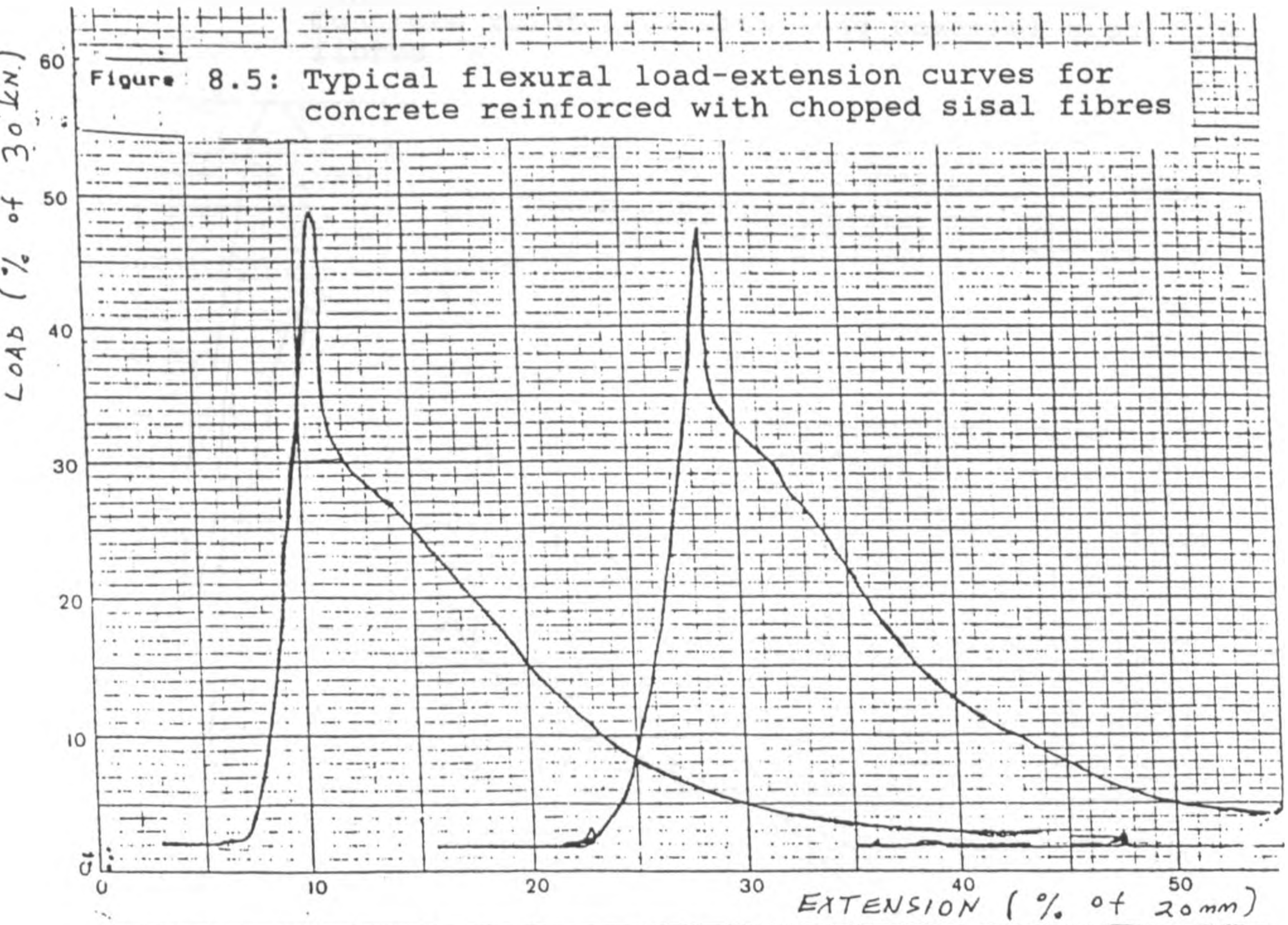


Figure 8.6: Typical tensile load-extension curves for concrete reinforced with chopped sisal fibres

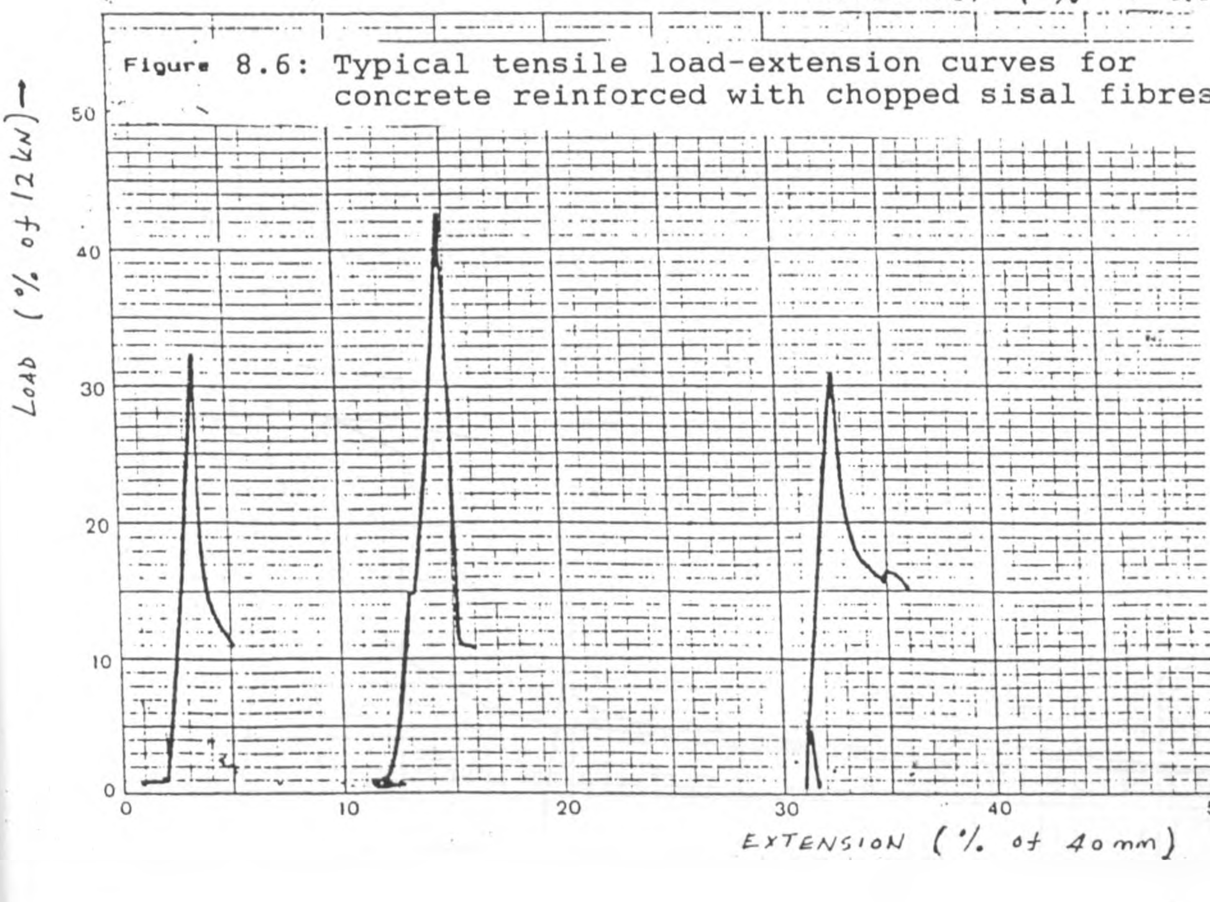


Figure 8.7: Typical flexural load-extension curves for concrete reinforced with long parallel sisal fibres

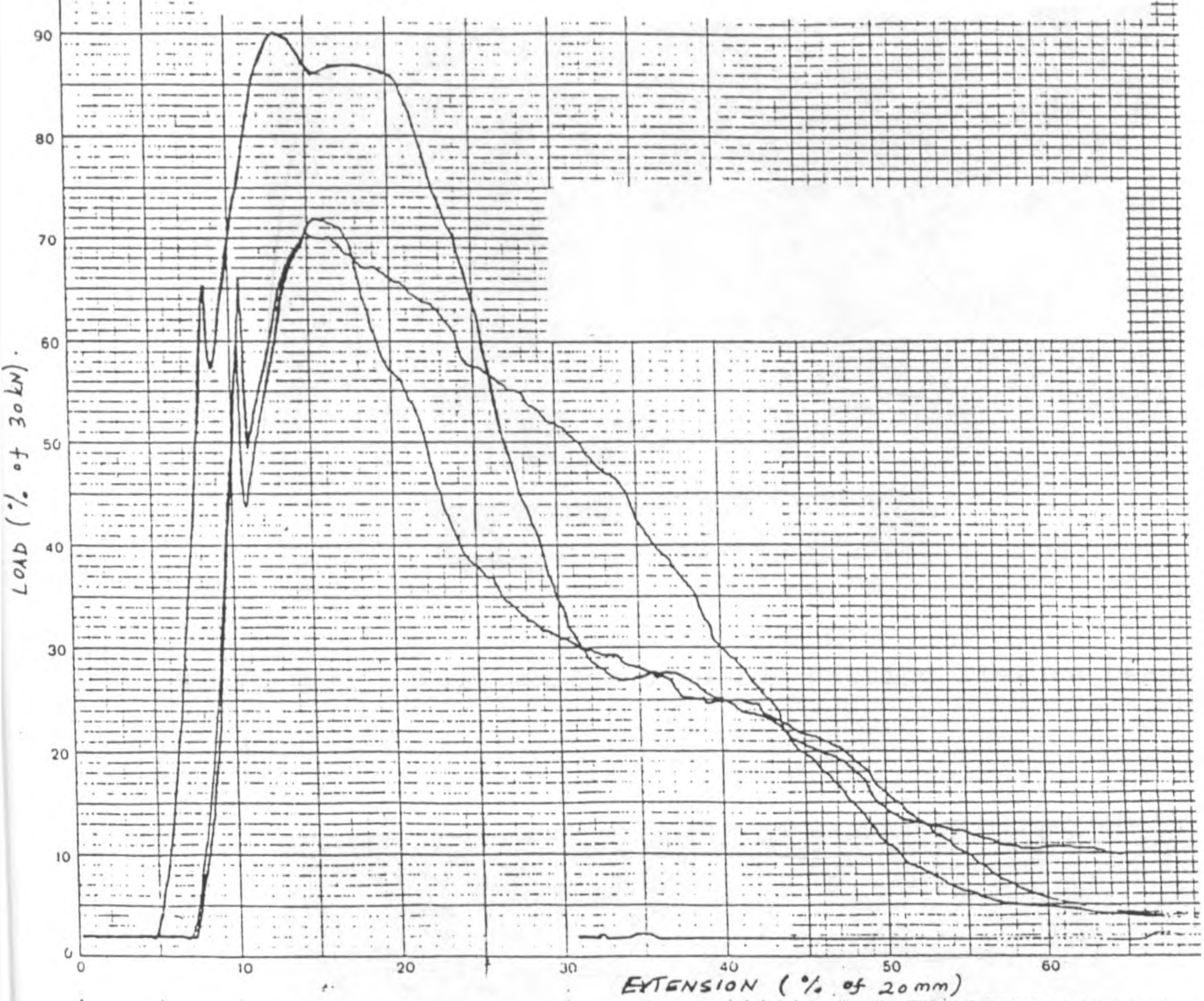
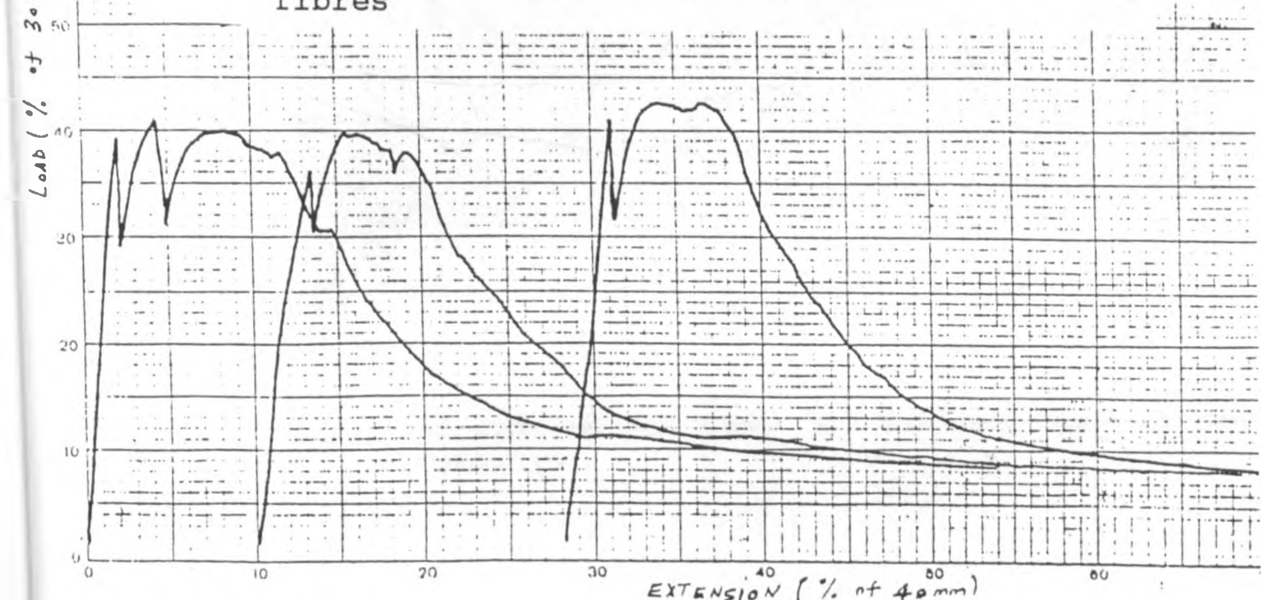


Figure 8.8: Typical tensile load-extension curves for concrete reinforced with long parallel sisal fibres



Appendix D : Plates.

Plate 8.1: Steel moulds used for casting flexure beams.

Plate 8.2 : Wooden moulds used for casting Tensile test samples

Plate 8.3 : Completely cured flexure beams ready for testing.

Plate 8.4 : A Flexural Test in Progress.

Plate 8.5 : Unreinforced samples after failure showing the failure sorface

Plate 8.6 : A parallel fibre reinforced sample after flexural failure

Plate 8.7 : A Tensile test in progress.

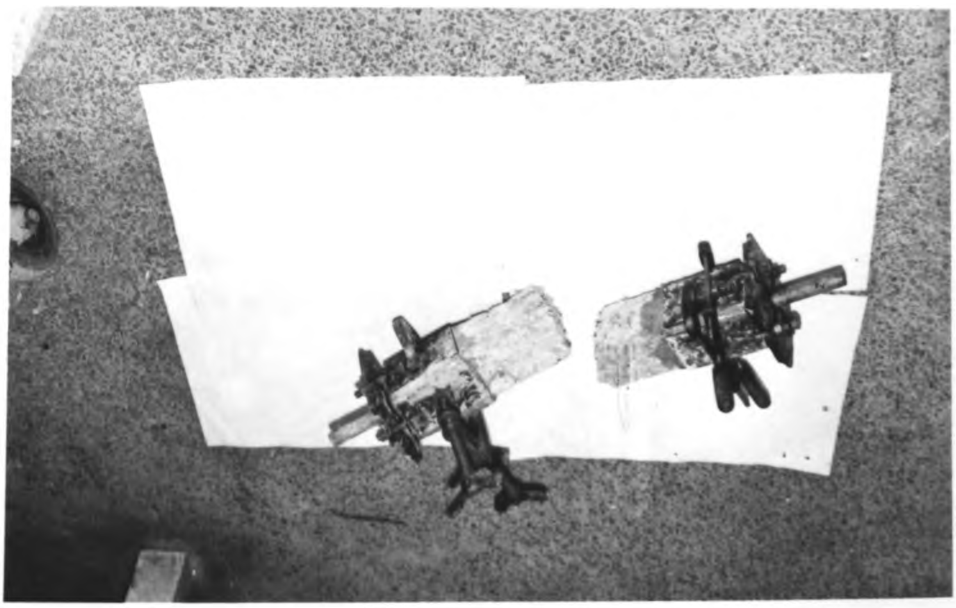


Plate 8.8 : Broken pieces after failure in tension.

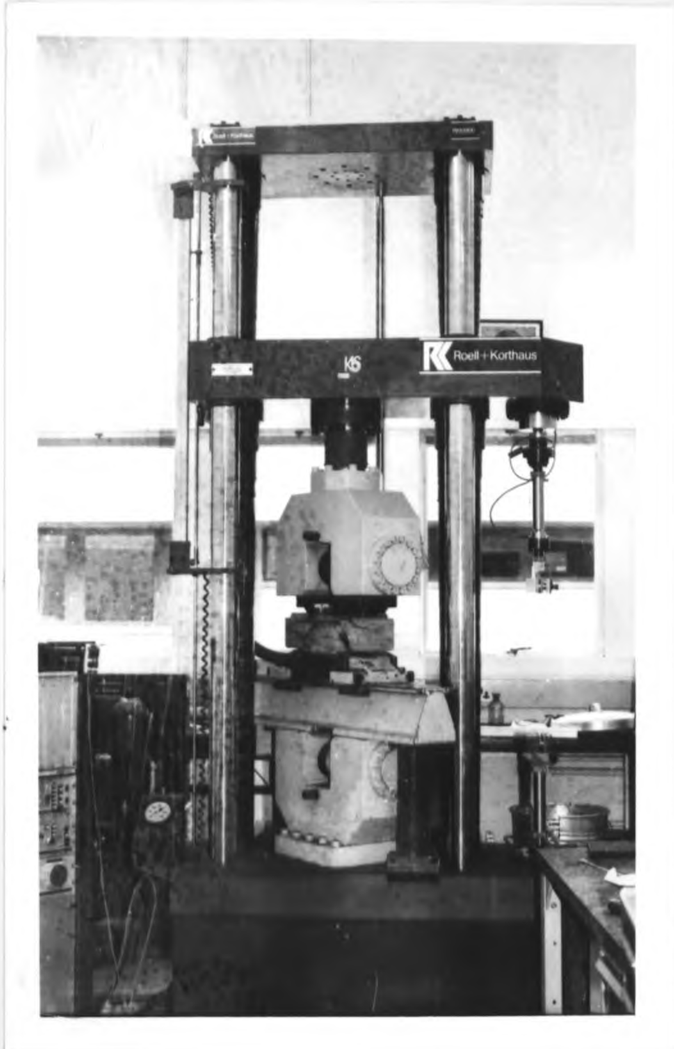


Plate 8.9 : The Universal Testing Machine with a flexure beam in place