UNIVERSITY OF NAIROBI

DETERMINATION OF STRUCTURAL PROPERTIES OF NATURALLY DRIED KABETE BLUE-GUM TIMBER

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DECLARATION

This thesis is my original work and has not been submitted for a degree in any university.

Signature_______________________Date 5/9/2000

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This thesis has been submitted for examination with my approval as university supervisor.

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DEDICATION

To my parents,

Roseline and Kiplagat Taragon;

they are professors in their own right.

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ABSTRACT

For several years, Blue-gum has been used for non-structural purposes. Its usage as a structural material has been inhibited by lack of its engineering properties. With its abundance coupled with the sky rocketing prices of other structural materials, availability of its properties will enhance its utilisation as a structural material. This study was done to meet this goal.

In this study, the following engineering properties of Blue-gum were evaluated; tensile, compressive, and bending strengths; and viscoelastic behaviour. Thirty test were carried on small clear specimens of dimensions 100 mm x 15 mm x 10 mm, 100 mm x 20 mm x 20 mm and 360 mm x 35 mm x 20 mm for tensile, compression and bending respectively. For viscoelastic behaviour, specimens used were of sizes 300 mm x 20 mm x 20 mm. The results indicates that Blue-gum timber has tensile strength of 123 MPa, compressive strength of 49 MPa and bending strength of 86 MPa. This strength values were obtained at moisture content of 17%. Blue-gum timber was found to be linearly viscoelastic at a stress equivalent to a third of ultimate bending strength.

The study concluded that with high values of strength and the ability to predict its time-dependent behaviour, Blue-gum timber is a good structural material.

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CHAPTER ONE

1.0 INTRODUCTION

Only about ten per cent of total land area of the African continent was covered with forest as per 1979. Tropical hardwoods comprised about ninety per cent of the forest, with temperate hardwoods accounting for about three per cent and softwoods only one per cent (TRADA, 1979). In Kenya, about 3.2 per cent (18,700 km^2) of land was under forests in 1991 and this value was bound to fall due to indiscriminate felling of these trees and that establishment of the same through afforestation take considerable time (Kimanzi, 1991). It was predicted (Ondimu and Gumbe, 1997), that Kenya is bound to suffer serious shortage of softwoods timber in ten years if the trend of their consumption was not checked. They proposed diversification of other timber sources to counter the looming crisis.

The trees grown under agroforestry systems have significant roles especially in Kenya and other tropical countries. Trees provide environmental protection, building materials, energy as charcoal and fuelwood, shade and aesthetic and food for both human and livestock. These forest are under risk of massive deforestation which has intensified lately. Infact the rate of their removal has long superseded the replacement rate. Their demand has risen due to the overgrowing population (Mark, 1991). This has necessitated the need to create awareness for proper utility of tree products by having a wide knowledge of their properties.

However, steps have been put in place by the government and industries to establish forest plantation which will provide tree products for industry, parts of urban population and very small portion of rural people. As a means of countering this depletion of forest, it is essential that, qualities of potentially useful trees and their timber be thoroughly examined (Mark, 1991). Timber as a major building material is in a greater demand, as a consequence, there is need for wide knowledge of their mechanical properties besides the wider need of knowing their expansive use.

Timber being orthotropic material has properties which are direction dependent. This implies that for a given desired qualities it is important that the nature of sawing must be considered (Tsoumis, 1991). Usually, sawing along the grains provides most if not all the desired properties. Durability, or resistance to decay is important when timber is selected for certain uses where conditions are favourable for decay to develop. In almost all the cases, strength of timber will depend on its density and moisture content being the factors affecting its properties.

Timber vary in their properties and appearance per species. Besides this, there is also variation within species and in geographical growth area. Sawn timber has variation in quality due to the state of growth and developmental requirements. Of importance is the soil and climatic conditions which affect the rate of growth, structure and strength properties. Timber obtained from trees of humid climates will have low density and conversely true for those from arid regions (Njogu, 1984). This variability has inherently affected their economic utilization. The knowledge of the properties of timber has been useful in laminating, jointing and framing, seasoning, and for protection against decay through fungi and insects. Due to this, timber continues to provide a wide range of uses as a structural material (Kagombe *et al*, 1994).

The properties of a given material in most case depends on the material structure in sense of atomic, molecular, microscopic and macroscopic levels. These properties may have been determined and are available in catalogues and handbooks; and a designer needs only to refer to them (Pascoe, 1982). However, not all the properties of a given material have been determined. Further, the available properties might be related to area of growth and thus of definite usage. This is very true especially for timber from tree species which grow in varied ecological zones (Grewal, 1986).

Properties may be derived from known values of related species. This, however may limit the accuracy at which the design work is made. This may increase risk of building collapsing or any other structural failure. Increase in accuracy in design work requires that exact determined properties of a given material be used. This helps to increase factor of safety and more so to enable a viable structures to be designed.

1.1 The Need for Timber Properties

Throughout the world, increasing attention is being given to material resources required to maintain and improve the present standard of living, to the energy needed to sustain community and other activities. The use of a particular resource will depend on several factors including its availability and renewability, the disturbance to the environment entailed in its extraction or harvesting, and the amount and type of energy required in its production, subsequent processing, application and disposal (Hills and Brown, 1984). Wood based materials are more attractive in this respect than most alternative materials. The amounts of raw materials required and cost of protecting the environment at all stages up to the preparation of products such as building materials are much less with wood than aluminium, steel or concrete.

One of the limiting factors in design work, is the scarcity of knowledge on the properties of materials. We need to know these properties so as to enable one to determine their interactions as the material is subjected to different types of loads. For any given material, its usage is determined by known properties. This means that a material remains useless so long as its properties are not available.

By having a wide field of properties, the scope at which a material will be used increases. In particular, timber which is a good building material may have better qualities in terms of strength when used in certain sections of a building or a structure than most other material in use today. Timber from Blue-gum has been used as a hardwood species in Kenya with its usage being limited by inadequate knowledge of its properties (Konuche, 1984). By increasing the number of known properties, wide utility of these species is enhanced. This in itself implies that the diverse usage of other species for the same task will be reduced and thus decrease in deforestation.

In the past, timber as a structural material has had little or no importance placed on it. Its greatest importance is of non-structural purposes as in manufacturing of furniture and very little collective work on the subject of timber properties related to usage have been carried out (Kimanzi, 1991). However, at present, there is a rapid growth in timber engineering catapulted by its abundance coupled with the sky rocketing prices of other structural materials. This has called for the need for information pertaining to timber to be presented in way which can be usefully be utilised by structural engineer. In this regard, it is imperative to determine properties of a material based on growth locality and intended usage. Enlarged use of hardwoods such as Blue-gum will limit the use of softwoods and thus decreased deforestation.

The choice of timber as a structural material , has been pegged upon (Milner and Bainbridge, 1999), the little energy required to convert wood to timber, its high strength to weight ratio, its abundance; and the ease in cutting, fixing and adaptability to site alteration Inspite of these advantages, the authors contends that timber usage has been inhibited by lack of education on its real benefits and the misconception that timber is a low technology product to be learnt through 'on-the-job' training and experience

In view of the fact that softwood timber have mostly been used in farmhouse (Boyd, 1979), there is need to diversify the use of hardwoods by increasing availability of scope of their properties. Timber from Blue-gum has predominantly been used for poles and no tangible evidence to show cause as to why it has not been used in construction industry. An outright reason could be that data on its properties have been limited (Campbell and Malde, 1971). The availability of such properties will enable a more understanding of its economical usage and more so, effective modes of treatment to obtain a good quality product.

The study of load deformation behaviour of timber in the natural state provide useful data in engineering analysis and design (Madsen and Barret, 1976). Most farm timber structures operate at heavy loads and are supposed to withstand these loads over a length of time. Safety and economical operation of these structures lies squarely on the accuracy of assessing the possibility for structural failure. The time-dependent deformation behaviour must be known so as to enable estimation of the life span of a given structure.

Despite the fact that experience and availability dictates which species of timber should be used for particular purpose, more detailed information on the properties of timber is required for efficient use, exploitation of unfamiliar timber and to aid in the selection of species for afforestation (Njogu,1984). Knowledge of its properties and behaviour under various conditions of service and treatment, is important in any design work. Most failures arising from the use of timber as a structural material have been attributed to ignorance about its properties.

It is hoped that through this study, by availing the properties of Blue-gum, its structural usage will be enhanced.

1.2. The Study Objectives

The broad objective of the study was determine the structural properties of naturally dried Kabete Blue-gum timber. The specific objectives of the study were to determine:

1 Tensile strength;

2 Compressive strength;

3 Bending strength;

4 Creep Compliance; and

5 Relaxation Modulus.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 General Overview

The Eucalyptus is increasingly considered by researchers and planners to be the most important tree available to man's exploitation, for its climatic adaptability, relative ease of establishment and wide ranging usefulness (FAO, 1981) The general characteristics of timber under study, Blue-gum (*Eucalyptus saligna*) includes; Sapwood about 50 mm wide, pale yellow in colour, fairly well defined from the light rose-brown hardwood. The grain is usually interlocked, occasionally straight and the texture is rather coarse. The wood has density of 938 kg/m^3 when dry. Strength properties are similar to those of other species. for example Karri (*Eucalyptus Diversicolor F. Muell*). Uses include; general construction, flooring, weather boards, boat building, wagon construction, fencing and for plywood, for which the veneer needs care when drying. Both tannin and leaf oil can be extracted from the tree for varied usage including medication (TRADA, 1979)

Kenya has an extensive experience with eucalyptus. They have played an important role in providing fuelwood, building poles, transmission poles, plywood and pulpwood. They were introduced in the country by the colonial government to provide fuelwood and railway slippers (FAO, 1981). The grown species were *Eucalyptus saligna* Sm and *Eucalyptus grobulus* Labill. The former was mainly planted at altitudes of 1600 above sea level while the latter was planted above this elevation. Both species survived under annual rainfall of 750 mm to 1800 mm. The spread of *E. globulus* was checked by eucalyptus snout beetle (*Gonopterus scitellatus*). At present, most regions is littered with *Eucalyptus saligna* and a combination of other species (Konuche,1989)

2.2 Strength of Timber

The resistance of timber to external applied force depends on the force magnitude, the direction of loading in respect to axial, radial or tangential and the manner of loading (Tsoumis, 1991). The effect of directional loading leads to timber having different engineering properties. For this, wood is anisotropic while its timber may be taken to be orthotropic.

Timber has a high strength : weight ratio both in tension and compression, and is elastic. It is able to sustain greater loads for a shorter while than it can over a long periods so that in deriving working stress values from test results, the rate of straining must be taken into account. Generally, strength increase with density, particularly within species. It reduces as moisture content rises and $1^{0}C$ rise in temperature reduces strength by about 0.3 per cent (Wangaard, 1950).

There is a wide variation between strength properties of species, between trees of the same species and in different parts of the tree. Defects, size and shape of specimens; and type and distribution of loading also affect strength. Parallel to the grain, tensile strength may be two or three times the compressive strength while strength in tension along the grain may be as much as thirty times that across the grain (Everett, 1970).

Borgin *et al* (1979), observed that mechanical stress originating from externally applied loads, or developing when timber looses or absorbs moisture, if adequate enough, may cause a permanent deformation of timber cells; such deformation results in secondary change (reduction or increase) of shrinkage and swelling. Large compression results in shrinkage greater than normal, when cross-sectional cell dimensions are permanently reduced. Inversely, under influence of large tension stress, shrinkage becomes smaller than normal.

2.2.1 Tensile Strength

There are various attempts that have been under taken to theories the strength of timber in tension. Early investigation (Mark, 1967) assumed that lignin and hemicellulose played no significant role in strength of timber. The models used to simulate strength in timber comprised of a series of endless molecules. The strength value obtain was of order 8000 MPa In modern modelling (Dinwoodie, 1994), finite length of cellulose and presence of amorphous regions have been taken in account. Minimum tensile stresses of order 1000 MPa to 7000 MPa have been derived using this technique. The ultimate tensile strength of timber is 100 MPa - though it varies with species. This value is about 1.5% to 10% of theoretical value of cellulose fraction. It is assumed here, that cellulose occupies about a half of timber weight. By this then, it can be taken that the strength of timber lie between 3% to 20% of theoretical strength.

Tensile strength is greatest in longitudinal axis (Silvester, 1967). This is dependent on strength of its fibres, their length and orientation. The fibre strength itself is governed by density of wood tissue and make-up of cellwalls. As stated earlier, the substance which provides the main tensile strength of timber is cellulose. Cellulose molecules are arranged in the form of chains which lie in the direction of longitudinal axis of fibres.

According to Kollmann and Cote (1968), strength in axial is much higher - up to fifty times and more than other directions. In the transverse direction the influence of radial or tangential load is not consistent. The values of strength in axial tension of temperate woods vary from 50 MPa to 160 MPa whereas in transverse tension the range is 1 MPa to 7 MPa. Though in some timber axial tension may reach 300 MPa. With the above values of axial tensile strength, especially the larger ones, Knigge and Schulz (1966), notes that this strength of timber compares favourably with metals and other building materials. The comparison is favourable for timber if strength is related to weight, (that is, weight for weight) is about equal to steel and superior to other construction material. Inspite of this the higher axial tensile strength of timber is seldom utilized, because of development of shear stress together with axial tensile stress.

2.2.2 Compressive Strength

The strength in compression of timber is provided by its lignin content as lignin acts as a stiffening agent to the cellular structure of the wood and cements it together into a coherent mass (Silvester, 1967). The strength of timber in compression is also different if loads are applied parallel or transverse to the grain. Axial compression is higher - up to fifteen times and varies between 25 MPa to 95 MPa whereas for transverse vary between 1 MPa to 20 MPa. It has been observed that in softwood timber, tangential compression strength is higher than radial, whereas in hardwood timber, the opposite is true (Dinwoodie, 1994). He notes also that, the failure of timber due to axial compression may be traced to rupture of intercellular layers, cleavage or shearing, bulking or folding of cells and rupture of cell walls.

2.2.3 Shear Strength

Shear may exist in longitudinal or transverse planes. Longitudinal shearing stress are present when timber members are stressed in bending. The strength varies from 5 MPa to 20 MPa (Silvester, 1967). The strength of timber in axial shear has the greatest practical importance Under the influence of shearing loads, wood usually fails in this manner. The strength of timber is usually expressed by the modulus of rupture, which shows the highest stress in outer most fibres of timber when the beam breaks under the influence of a load, which is applied gradually for a few minutes (Wangaard, 1950). Modulus of rupture varies between 55 MPa to 160 MPa - indicating to be similar to axial tension. For this reason, modulus of rupture may be used as an index of strength in axial tension, if values of the latter are not available.

The strength of timber in axial shear has the greatest practical importance because under the influence of shearing loads, timber usually fails in this manner, consequently the high axial tensile strength of timber is seldom utilised due to development of shear stresses.

Most research done for Blue-gum are limited to bending tensile and compressive strengths. The work of Ondimu and Gumbe (1997) on structural specimens, obtained mean values of 55.1 MPa , 68.1 MPa and 31.3 MPa for the above respectively. Kagombe *et al* (1994) obtained values of 52.2 MPa and 62.4 MPa for compressive and tensile strengths respectively. Values of modulus of rupture and modulus of elasticity of 1.14 MPa and 2.59 MPa were obtained from 24 test done by Campbell and Malde (1971).

2.2.4 Viscoelasticity

(a)Creep Behaviour

Some general observations about creep in wood indicates that wood behaves non-linearly over the whole stress-level range, with linear behaviour being a good approximation at low stresses

(Schaffer, 1972). Because of this nearly linear response at low levels of stress, Boltzmann's superposition principle applies to stress-strain behaviour for stresses up to 40% of short time behaviour. This implies that under long term loading when stress, moisture content and temperature are sufficiently low, wood will act essentially in linear elastic manner; at intermediate values of these variables its behaviour becomes linear viscoelastic in nature, and at higher stress levels, or in fluctuating environment conditions, wood becomes distinctly non-linear viscoelastic in character (Whale, 1988).

The work of Wood (1951), indicates that the relationship of load over time is slightly curvilinear and that there is a distinct levelling off at loads approaching 20 % of the ultimate short term strength such that a critical load or stress level occurs below which failure is unlikely to occur. The predication of creep response using small clear specimen differ as in large sized timber Madsen and Barret (1976), found out that at higher stress ratios, the load duration effect is severe on large sized than small clear test specimen.

The magnitude and rate of creep in timber at higher moisture content is higher than when dry (Hearmon and Paton, 1964). Their work also indicates that timber under load with high moisture content shows cyclic deformation when moisture is cycled from wet to dry and then back to wet. Further, the higher the moisture differential in each cycle, the higher amount of creep.

Creep in timber has been expressed using mathematical equation which are in most cases empirical and may have a small degree of theoretical backing. In fact their use is a function of how well their constants may be determined and further the ease at which it suits the experimental data. Dinwoodie (1994) believes that the most successful mathematical expression is of the type:

$$\varepsilon(t) = \varepsilon_0 + at^m \tag{2.1}$$

Where **ε(t)** is the time-dependent strain, **ε_o** is the initial elastic deformation, **a** and **m** being constant (**m** = 0.33 for timber), and **t** is the elapsed time.

Gressel (1984), using data obtained from a period of ten years test, tried four different creep functions:

$$\varepsilon(t) = \beta_1 + \beta_2(1 - e^{-\beta_3 t}) + \beta_4 t \tag{2.2}$$

$$\varepsilon(t) = \beta_1 + \beta_2(1 - e^{-\beta_3 t}) \tag{2.3}$$

$$\varepsilon(t) = \beta_1 t^{\beta_2} + \beta_3 \tag{2.4}$$

$$\varepsilon(t) = \beta_1 t^{\beta_2} \tag{2.5}$$

He found out that the 4-element parameter creep model has its functions highly correlated with both loads and environmental conditions, as well as each other. The 3-element model was not relevant because it incorrectly assumes no further creep beyond the last data point. Although 4-element model gave satisfactory results, it predicts too high deflection; for it assumes a constant rate of viscous creep after the last data point.

Creep is known to be affected by temperature and moisture. Moisture is also a function of the environmental relative humidity. An increase in temperature will generally reduce the stiffness of timber in bending, compression or tension (Bach and McNatt, 1990) especially above 55 °C. This is the temperature where lignin alters its structure and hemicellulose begin to soften.

A complex creep behaviour may be obtained with variable temperature. This behaviour is hard to predict. The work of Jouve and Sales (1986), showed that an increase in temperature in the range of 20 °C to 90 °C during a bending test resulted in creep larger than creep caused by constant temperature at the highest level.

The effect of moisture in wood is that, it acts as a plasticizer. This leads to the fact that creep increases with moisture content. Bach (1965), found out that in tensile test, with varying moisture content (from 4% to 14%), the creep compliance was proportional to square of moisture. He relates the effect of moisture with temperature that; an increase of moisture content by 4% has the same effect as when temperature is increased by 6 °C within the moisture and temperature limits of the experiment.

The mechano-sorptive effect on timber under creep test does not seem to have a particular time dependent phenomena (Grossman, 1978).

(b)Stress Relaxation

Timber, like concrete and high polymers depict time-dependent behaviour (Dinwoodie, 1974). The strain magnitude arising from stressing the material is influenced by a wide range of factors. Some of these are property dependent, such as density, angle of the grain relative to the direction of load application, angle of microfibrils within cellwall and others are environmentally dependent; that is, temperature and relative humidity.

Bach (1965), did stress relaxation on Doughlas fir at 8% moisture content and 22 °C and found that when strained to 99% of estimated ultimate strain before allowing the samples to stress relax; over 50% failed within a period of seven days.

2.3. Factors Affecting Timber Strength

There are many factors influencing the strength of timber. Most importantly is the moisture content and density which is a function of anatomical make of timber. Other factors as environmental temperature play a significant role in determining the strength of timber as well.

2.3.1 Moisture Content

There is a correlation between moisture and strength of timber. Increase in moisture reduces the strength and the converse is true (Stamm, 1964). The increase in strength in moisture reduction has been explained by the fact that cellulose, which is a major structural component of timber, always exhibits greater strength when dry than when wet. The greater strength when dry is derived from three causes; one is that cellulose's structural units - the microfibrils, become compact thus increase in attractive forces. Secondly the moisture acting as a lubricant reduces the frictional resistance among the cellulose, consequently when removed the verse visa holds. Lastly, reduction in moisture leads to shrinkage, meaning increase in mass per volume of wood (density increases). Although the change in strength with change in moisture content follows similar trend for most strength properties, the magnitude of the changes varies from one property to another (Lavers, 1969). For instance compression strength changes relatively higher than bending strength.

The variation of strength with moisture may be represented by a mathematical expression. For example, for compression studies, Wilson (1932), represented this relationship within certain limits, as the logarithm of the strength and corresponding moisture content:

$$\log s = \log s_p + k(m_p - m) \quad (2.6)$$

Where **s** is the strength corresponding to moisture content **m**, and s_p and m_p are the strength and moisture content respectively at the fibre saturation point, **k** being a constant

When comparing strength properties of timber, there is need to determine properties at constant moisture content. Otherwise, properties determined at different moisture content need to be corrected for the use of comparison while assuming that the moisture content is uniformly distributed in the wood mass.

2.3.2 Density

This is the best indicator of strength in timber especially on clear test specimen. Strength is positively correlated to the amount of wood substance and its variation explains the differences in strength. The relation of density and strength properties in species in most cases is linear (Lavers, 1969). As much as density may be considered a clear indicator to strength, caution should be taken when other factors such as abnormal growth characteristics and knots are in play. This may increase the total mass but not the strength (may reduce).

As in moisture content, density may be related to strength. The relationship as given by Wangaard (1950) is of the form:

$$\frac{S}{S'} = \left\{\frac{G}{G'}\right\}^n \quad (2.7)$$

Where **S** and **S'** are values of strength corresponding to densities **G** and **G'** and **n** is a constant varying between 1.25 and 2.50 depending on the property.

Dinwoodie (1994) proposes that the relation of density with strength may be given thus:

$$S = kG^n \tag{2.8}$$

where **S** is the strength property, **G** is the specific gravity, **k** is a proportionality constant differing for each property and **n** is the exponent that defines the slope of the curve of property versus specific gravity.

2.3.3 Anatomical Features

Wood characteristics that affect density, does affect its strength. The rate of growth defines the growth rings. A fast growing tree is bound to have lower density as compared to slow growing tree. Sometimes this may not hold true, since proportions of early and latewood may have significant effect (Dinwoodie, 1994). Further, irregular thickening of growth rings associated with compression softwood or tension hardwoods may in effect affect density.

The slope of grain has a profound effect on strength. The way a tree grow affects the orientation of its fibres (Desch and Dinwoodie, 1981). Grains may be spiral, diagonal or a mixture of the two. Strength will always be high along the grains for tensile strength and at right angles on its radial and tangential axes for compressive strength.

The effect of grain slope on strength properties is more appreciated when considering design in structural work - to be able to predict with reasonable degree of accuracy, the strength in order to save guard working stresses.

2.3.4 Defects of wood

The leading defect in timber is the knots (Silvester, 1967). Knots appearing on timber results from formation of branches in the tree trunk. The effect of knots is the deviation of grains and checks arising from its presence. The grain disturbance brings in the weakening effect and infact it is not the knot that matters but the amount of grain disturbance it causes. The disturbance is a function of size, grouping, location and orientation of the knots in timber.

The effect of the presence of a knot in a piece of timber is to reduce strength in proportion to the area of the cross-section it occupies, grain disturbance to dimensions of the piece and influence of its orientation and location.

In general, the diameter of knots has a greater effect than their number. Further, the effects of holes arising from falling out of encased knots is different from that of directly opened by tools (Kollman and Cote, 1968). In axial tension, knots have the highest effect in comparison to other loading modes.

Abnormal growth of a tree leads to development of reaction wood. This result from the wood resisting external forces which are greater than what the tree is normally subjected. They are of two kinds; tension and compression woods. Their presence may have positive, negative or no effect on the strength of timber.

Compression wood is inherently weaker than normal wood in majority of its strength properties due to the fact that in its initial stages a form of incipient mechanical failure had occurred during growth period. Though the nature of loading, species of wood and extent of abnormality may determine the effect on strength (Perem, 1960).

In general, abnormalities are considered to have negative effect on strength due to the fact that they cause checks or warping with change in moisture content- brought about by high axial shrinkage.

Fissures (shakes, checks and splits) are other defects of wood which affect timber strength. The effect of shakes and checks on strength properties is important because they reduce the area resisting shear (Silvester, 1967). Consequently with these defects shear strength is reduced.

2.3.5 Temperature

Strength of timber is reduced with increased temperature and that the strength - temperature relation is different for various properties. The relationship is non-linear for compression while for others its linear (Comben, 1964). Experimental results obtained by the same author, on the relationship of stiffness and temperature is curvilinear, though the degree of curvature is slight at lower moisture content. At this level, the relationship may be linear thus:

$$E_T = E_t[1 - a(T - t)] \tag{2.9}$$

Where **E** is the elastic modulus, **T** is a higher temperature, **t** is a lower temperature and **a** is temperature co-efficient.

The duration of heating is very important. Temperatures lower than 100 °C have no effect for a shorter time while temperature above 65 °C for a longer duration may have permanent effects on strength reduction (Galligan, 1975).

CHAPTER THREE

3.0 THEORETICAL ASPECTS

3.1 Stress

Stress is the intensity of a force (load) acting in a given a body. The three-dimensional state of stress at a point in a stressed body is described with respect to three arbitrary orthogonal planes passing through that point (Findley, *et al*, 1976).

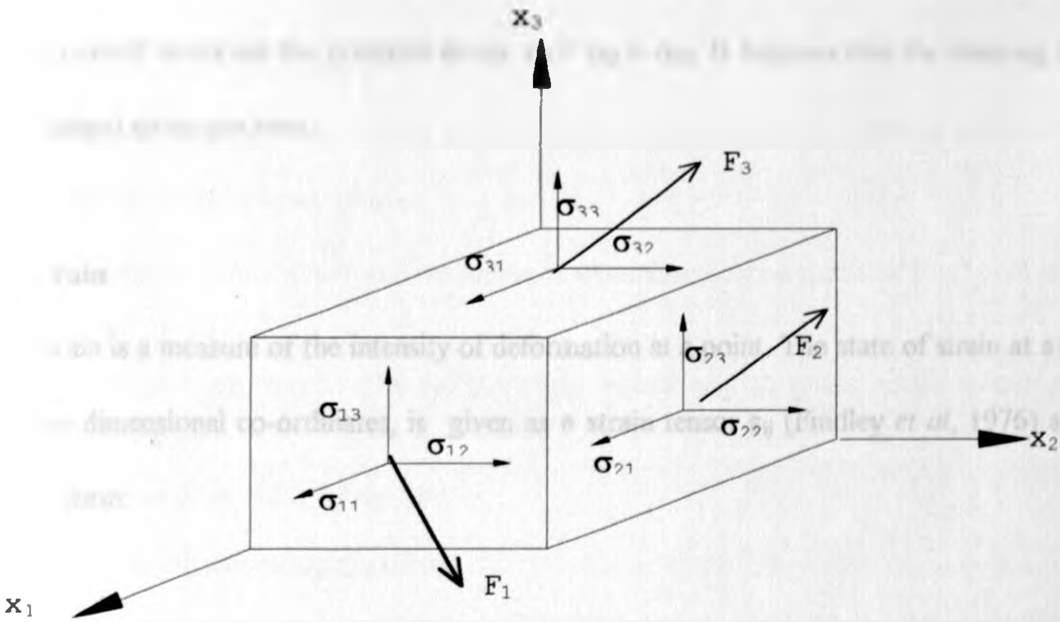

Figure 3.1. Stress Components of a General State of Stress

The nine components σ_{11} through σ_{33} involved in describing the state of stress above constitute a stress tensor given as σ_{ij} and in matrix form:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \quad (3.1)$$

Where i - indicates the plane, j - indicates the direction and i, j - takes the values of 1,2 and 3

It has been established that $\sigma_{12} = \sigma_{21}$, e t c; implying that the stress tensor is symmetrical about the diagonal line σ_{11} to σ_{33} or $\sigma_{ij} = \sigma_{ji}$ and thus there are only six independent components of stress describing the state of stress.

A particular set of orthogonal planes will be found for which one of the normal stresses σ_{11}, σ_{22} and σ_{33} is a maximum and one is minimum with respect to the rotation of co-ordinates. These normal stress are the principal stress $\sigma_{I} > \sigma_{II} > \sigma_{III}$. It happens that the shearing stress on principal stress are zero.

3.2 Strain

The strain is a measure of the intensity of deformation at a point. The state of strain at a point in three dimensional co-ordinates, is given as a strain tensor ε_{ij} (Findley *et al*, 1976) and in matrix form:

$$\varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \quad (3.2)$$

This is a second order cartesian tensor and the subscript notation has the same significance as in stress tensor.

In view of the similarity of strain tensor and stress tensor it follows that all stress relationship that may be derived from the stress tensor have a counterpart for strain.

3.3 Mechanics of Stress and Strain in Analysis

The mechanical behaviour of continuum is governed by certain physical laws. These laws may be common to all continuous materials while others are intrinsic properties of each group or each individual material (Gumbe, 1993). Some of these laws are; conservation of mass, balance of momentum, balance of moment of momentum, conservation of energy, constitutive relations and principles governing thermodynamics. When analysing stress in a continua, the solutions of a system of equations involves; equations of equilibrium , strain relations, compatibility relations, constitutive relations and boundary conditions.

3.3.1 Boundary Conditions

A material under stress analysis may have the following three specified boundary conditions (Findley *et al*, 1976);

1. Specified traction: The force per unit area of surface may be specified for the whole or part of the body.
2. Specified displacement: The surface displacement may be given on the whole or part of body
3. Mixed traction and displacement.

3.3.2 Constitutive Equations

Constitutive equations are equations which characterise an individual material and its reactions to external excitations. Real materials behave in such a complex ways that when the entire range of possible temperature and deformation is considered it is presently impossible to write down a single equation which will describe accurately the behaviour of real material over the entire range of variables. Instead, and idealisation approach is adopted where separate constitutive equations are formulated to describe various kinds of idealised material response. Each of these equations is a mathematical formulation designed to approximately describe the observed response of a real material over a certain range of the variables involved. Based on this a material may be characterised as; elastic, plastic, elastoplastic, viscoelastic, viscoplastic and elastoviscoplastic (Findley *et al*, 1976).

In studying stress - strain behaviour of materials, its important to note the following terminologies for describing a material (Gumbe, 1993);

1. A *homogeneous* body has uniform properties throughout, that is, the properties are not functions of position in the body
2. An *isotropic* body has material properties that are the same in every direction at a point in the body, that is, the properties are not functions of orientation at a point in a body
3. An *inhomogeneous* body has non-uniform properties over the body, that is, the properties are functions of position in the body.
4. An *orthotropic* body has material properties that are different in three mutually perpendicular directions at a point in the body and , further, have three mutually perpendicular planes of material symmetry. Thus the properties are functions of the orientation at all points.
5. An *anisotropic* body has material properties that are different in all directions at a point. There are no planes of symmetry. Again, the properties are functions of orientation at a point in the body

3.4 Stress - Strain Relationships for Elastic Body

Stress - strain relationships for linear elastic body was first proposed by Hooke. A linear elastic solid obeys the generalised Hookes' law; that stress tensor is linearly proportional to strain tensor (Mase, 1970). That is;

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \quad (3.3)$$

Where C_{ijkl} is a 4th order tensor - stiffness tensor describing the elastic moduli of the material

To determine explicit forms of elastic constants for an orthotropic material, Poisson ration, v is defined as,

$$\nu = \frac{-\varepsilon_{(ii)}}{\varepsilon_{(jj)}} \tag{3.4}$$

It follows then that the compliance C_{ijkl} is given (Chung, 1988) by:

$$C_{ijkl} = \begin{bmatrix} \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & \frac{-\nu_{31}}{E_3} & 0 & 0 & 0 \\ & \frac{1}{E_2} & \frac{-\nu_{32}}{E_3} & 0 & 0 & 0 \\ & & \frac{1}{E_3} & 0 & 0 & 0 \\ & & & \frac{1}{G_{12}} & 0 & 0 \\ & & & & \frac{1}{G_{23}} & 0 \\ & & & & & \frac{1}{G_{31}} \end{bmatrix} \tag{3.5}$$

Where **E** is the elastic modulus and **G** is shear modulus.

Timber is orthotropic because of its nature of the cells and the manner in which it is lumbered from its wood. The wood itself is anisotropic because during growth there is an outward diameter increase (Tsoumis, 1991).

When considering timber as orthotropic, we assume that the three elasticity directions coincide with longitudinal and tangential directions in the wood. That is the tangential faces are not curved and radial faces are parallel, not diverging (Dinwoodie, 1994). The orthotropic lamina of timber is as shown in Figure 3.1.

The stress - strain relationship for this orthotropic lamina (Hollaway, 1989) can be in matrix form:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{bmatrix} \qquad (3.6)$$

$$[\sigma] = [Q][\varepsilon]$$

Where :

$\sigma_{11} = [\varepsilon_{11} + v_{21}\varepsilon_{22}][E_{11}/(1-v_{12}v_{21})]$,

$\sigma_{22} = [\varepsilon_{22} + v_{12}\varepsilon_{11}][E_{22}/(1-v_{12}v_{21})]$,

$\sigma_{12} = G_{12}\varepsilon_{12}$,

$Q_{11} = E_{11}/(1-v_{12}v_{21})$,

$Q_{22} = E_{22}/(1-v_{12}v_{21})$,

$Q_{12} = v_{21}E_{11}/(1-v_{12}v_{21})$,

$Q_{21} = v_{12}E_{22}/(1-v_{12}v_{21})$, and

$Q_{33} = G_{12}$

The **Q** matrix is symmetrical, thus $v_{21}E_{11} = v_{12}E_{22}$ where poisson's ratio v_{12} refers to strain product in direction 2 when loading is in direction 1

Orthotropic properties of the timber lamina depends on four independent constants; E_{11}, E_{22}, v_{12} and v_{21}. The shearing stress σ_{12} is independent from these properties. The relationship of strains and stresses in matrix form is:

$$
\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{21} & S_{22} & 0 \\ 0 & 0 & S_{33} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \tag{3.7}
$$

$$
[\varepsilon] = [S][\sigma]
$$

Where :

$S_{11} = 1/E_{11}$, $S_{22} = 1/E_{22}$, $S_{33} = 1/G_{12}$, $S_{12} = -\nu_{21}/E_{22} = -\nu_{12}/E_{11}$

When loading does not coincide with the principal axes, the loading axis can be transformed to the principal axes, Figure 3.2

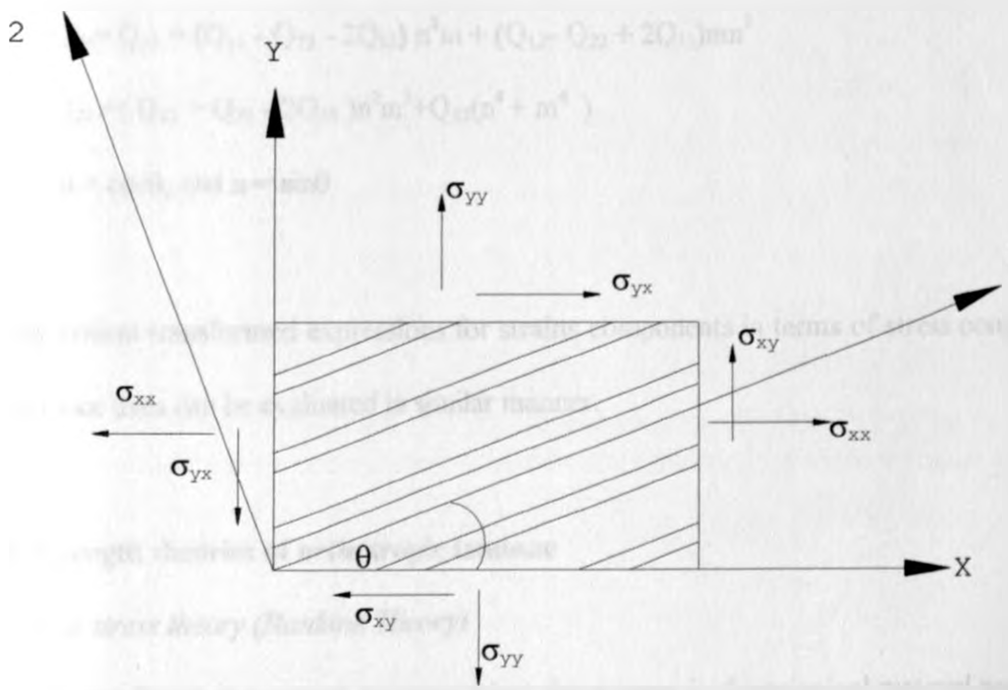

Figure 3.2. Orientation of orthotropic lamina about a reference axis

If θ is the angle between loading axis and principal material axes, the stress - strain relationship in matrix form is:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & Q_{13}\\ Q_{21} & Q_{22} & Q_{23}\\ Q_{31} & Q_{31} & Q_{33}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{xy}\end{bmatrix} \tag{3.8}$$

Where:

$Q_{11} = Q_{11}m^4 + Q_{22}n^4 + 2(Q_{12} + 2\,Q_{33})n^2m^2$

$Q_{12} = Q_{11} = (Q_{11} + Q_{22} - 4\,Q_{33})n^2m^2 + Q_{11}(n^4 + m^4),$

$Q_{13} = Q_{31} = (Q_{11} - Q_{12} - 2Q_{33})\,nm^3 + (Q_{12} - Q_{22} + 2Q_{33})n^3m,$

$Q_{22} = Q_{11}n^4 + Q_{22}m^4 + 2(Q_{12} + 2\,Q_{33})n^2m^2$

$Q_{23} = Q_{32} = (Q_{11} - Q_{12} - 2Q_{33})\,n^3m + (Q_{12} - Q_{22} + 2Q_{33})nm^3$

$Q_{33} = (Q_{11} + Q_{22} - 2Q_{33})n^2m^2 + Q_{33}(n^4 + m^4)$

$m = \cos\theta$, and $n = \sin\theta$

The equivalent transformed expressions for strains components in terms of stress components to reference axes can be evaluated in similar manner.

3.4.1 Strength theories of orthotropic laminae

Maximum stress theory (Rankine Theory)

In this theory failure is assumed to occur when the stresses in the principal material axes reach a critical value i.e yield value (Hollaway, 1989). This means there could be only three possible failure modes:

$$\begin{aligned}\sigma_{11} &= \sigma_{11}^{*}\\ \sigma_{22} &= \sigma_{22}^{*}\\ \sigma_{12} &= \sigma_{12}^{**}\end{aligned} \tag{3.9}$$

Where * indicates the ultimate tensile or compressive stress in directions 1 and 2 respectively while ** indicates the ultimate shearing stress in plane 1 in direction 2

When loading is at an angle θ, then after transformation, the values are:

$\sigma_{11} = \sigma_{xx} m^2 = \sigma_0 m^2$

$\sigma_{22} = \sigma_{xx} n^2 = \sigma_0 n^2$

$\sigma_{12} = -\sigma_{xx} nm = -\sigma_0 nm$

Failure in this theory depends on relative value of σ_{11}, σ_{22} and σ_{12} and thus the smallest of the three below:

$$\sigma_\theta = \frac{\sigma_{11}^{*}}{m^2} \qquad \sigma_\theta = \frac{\sigma_{22}^{*}}{n^2} \qquad \sigma_\theta = \frac{\sigma_{12}^{**}}{nm} \tag{3.10}$$

Maximum strain theory (Saint Venant Theory)

The theory assumes failure occurs when strains in the principal axes reach a critical value i e yield value. As in maximum stress theory, failure occur in three modes:

$$\varepsilon_{11} = \varepsilon_{11}^{*} \qquad \varepsilon_{22} = \varepsilon_{22}^{*} \qquad \varepsilon_{12} = \varepsilon_{12}^{**} \tag{3.11}$$

Where * indicates the ultimate tensile or compressive strains in directions 1 and 2 respectively while ** indicates the ultimate shear strains in plane 1 in direction 2.

3.5 Viscoelasticity.

Some materials exhibit elastic action upon loading, then a slow and continuous increase of strain at decreasing rate is observed. When the stress is removed a continuously decreasing strain follows an initial recovery. These materials are significantly influenced by the rate of straining and stressing. These materials are called viscoelastic. Viscoelasticity combines elasticity and viscosity i.e viscous flow (Findley *et al*, 1976).

In linear viscoelastic material the ratio of stress to strain is a function of time alone and not of stress magnitude. For a number of viscoelastic materials, linear viscoelastic response can be achieved experimentally if the deforming stresses are kept sufficiently small (Mohsenin, 1970). If the magnitude of stress is such that the resulting strain is mostly unrecoverable upon unloading, the viscoelastic behaviour is non-linear

Timber can be idealised as linearly viscoelastic and for such a material, according to Rumsey and Fridley (1977), the following two criteria holds:

1. (A) For any step input of stress σ_0, the relation between the strain $\varepsilon(t)$ and stress is;

$$\varepsilon(t) = \sigma_0 J(t) \tag{3.12}$$

Where **J(t)** is the creep compliance; creep strain per unit of applied stress

(B) For any step input of strain ε_0, the relation between the stress $\sigma(t)$, and strain is;

$$\sigma(t) = \varepsilon_0 E(t) \tag{3.13}$$

Where **E(t)** is relaxation modulus; the stress per unit of applied strain

2. Boltzann's superposition principle hold. That is the stress at any time t, depends on the strain history of the material. In equation form;

$$\sigma(t) = \int_0^t E(t-\tau)\frac{\partial \varepsilon}{\partial \tau}d\tau + \sum_{i=1}^{n} \Delta\varepsilon_i E(t-t_i) \tag{3.14}$$

Where **ε(t)** is applied strain and $\Delta\varepsilon_i$ are finite jumps in applied strain occurring at time t_i

According to Herum *et al* (1979), the response to a step input of deformation may be written in the form of Prony series as:

$$E(t) = \sum_{i=1}^{n} E_i e^{\frac{-t}{\tau_i}} \tag{3.15}$$

which can be represented as:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_i e^{\frac{-t}{\tau_i}} \tag{3.16}$$

Where $\mathbf{E_\infty}$ is the response after a very long time, $\mathbf{E_i}$ and τ_i are spring constant and time constant respectively.

3.5.1 Mathematical representation of viscoelastic behaviour

The stress - strain relationship for viscoelastic behaviour are sometimes empirical. Generally, they are developed to meet experimental data. Usually the data indicates that that behaviour of the material is affected by the magnitude and sequence of stress or strain in all of the past history of the material (Findley *et al*, 1976). Upon this, two methods have been employed to represent the viscoelastic behaviour of these materials.

(a) Differential form

The linear differential operator method can be used to give stress - strain relations in uniaxial stressing or straining. For example;

$$P\sigma = Q\varepsilon \tag{3.17}$$

Where **P** and **Q** each represent a series of linear differential operators, with respect to time, containing material constants. The material may be represented by a combination of mechanical models (springs and dash pots)

These models gives a simple and clear physical description of the fundamentals of viscoelastic behaviour. Solving a viscoelastic problem using linear differential equations requires that time variable in the system is removed plus boundary conditions, by using Laplace Transformation with respect to time. This makes the problem be an elastic problem. After algebraic operations, the solution is brought back to initial time variable by utility of Inverse Laplace Transforms. This may be difficult if the variables are many. However, this method is useful when the boundary conditions are specified by stress or deformation.

(B) Integral form

Any stress time curve may be approximated by the sum of series of step function which corresponds to a series of step - like increments load. The creep compliance **J(t)** may be defined as the creep strain resulting from the unit stress. Using Boltzmann's superposition principle, the strain ε **(t)** occurring during a creep test at time **t** may be expressed as;

$$\varepsilon(t) = \int_0^t J(t-t_1)\frac{\partial\sigma(t_1)}{\partial(t_1)}d(t_1) \tag{3.18}$$

Where $\mathbf{t_1}$ is any arbitrary time between **0** and **t**, representing past time. The kernel function of the integral $\mathbf{J(t-t_1)}$ is a memory function which describes the stress history dependence on strain. The stress - relaxation of linear viscoelastic material can be expressed in a similar way as equation (3.17) above.

3.5.2 Creep Behaviour

Creep is a slow continuous deformation of a material under constant stress. For uniaxial loading, creep may be described in terms of four main stages. An initial instantaneous extension, a stage of creep at decreasing rate, a stage of creep at an approximately constant rate, and a stage of creep at an increasing rate ending in fracture (Pascoe, 1982). The last three stages are usually referred to as primary, secondary and tertiary creep respectively. In creep test, a step input of constant stress, σ_o is applied and time-dependent strain $\varepsilon(t)$ is measured. For linearly viscoelastic material, (Findley *et al*, 1976) the strain can be represented by equation (3.12)

Creep behaviour in timber may be interpreted with aid of mechanical models consisting of different combinations of springs and dashpots (Morlier and Palka, 1994). The basic model attempting to explain creep, is the Kelvin model Figure 3.3 (c) (Mohsenin, 1970). This model consists of a Hookean element (a) -a spring and Newtonian element (b) -a dashpot.

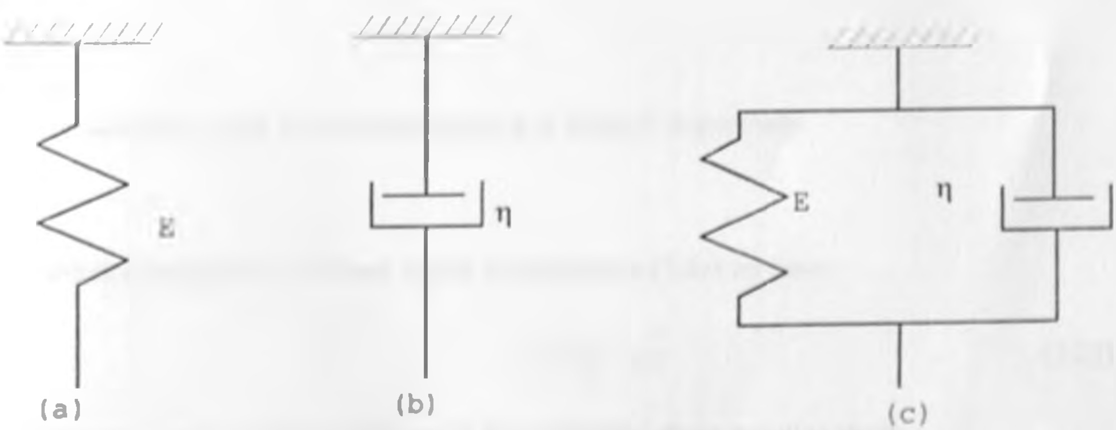

Figure 3.3. Hookean element (a), Newtonian element (b) and Kelvin Model (c).

For uniaxial tension or compression

$$\varepsilon_s = \frac{\sigma_s}{E} \tag{3.19}$$

Where ε_s is the lateral strain, σ_s is the applied stress, **E** is the modulus of elasticity and the subscript **s** represents the spring.

The dashpot represents linear relaxation shear and rate of shear strain is:

$$\frac{\sigma_v}{\dot{\varepsilon}_v} = \eta \tag{3.20}$$

Where σ_v is the shear stress, $\dot{\varepsilon}$ is shear strain rate, η is the viscosity of the liquid and the subscript **v** represents the dashpot.

Since stress is shared between the spring and dashpot, the strains will be the same i.e,

$$\sigma = \sigma_s + \sigma_v,$$

$$\varepsilon = \varepsilon_s = \varepsilon_v \tag{3.21}$$

Where subscripts **s** and **v** represents spring and dashpot respectively.

Substituting equations (3.19) and (3.20) in equation in (3.21) we have:

$$\sigma = E\varepsilon + \eta\dot{\varepsilon} \tag{3.22}$$

When the time of retardation is given by **Trt** = **η/E** the above equation yields:

$$\frac{\sigma}{E} = \varepsilon + Trt\,\dot{\varepsilon} \tag{3.23}$$

The above equation (3.23), when differentiated gives:

$$\frac{\dot{\sigma}}{E} = \dot{\varepsilon} + Trt\,\ddot{\varepsilon} \qquad (3.24)$$

Under constant load $\dot{\sigma} = 0$, equation (3.24) becomes,

$$\dot{\varepsilon} + Trt\,\ddot{\varepsilon} = o \qquad (3.25)$$

Integrating, we obtain

$$\varepsilon = \frac{\sigma_0}{E} + (\varepsilon_0 - \frac{\sigma_0}{E})e^{\frac{-t}{Trt}} \qquad (3.26)$$

Where σ_o is the initial load.

At t = 0, $\varepsilon_0 = 0$ and thus for creep,

$$\varepsilon = \frac{\sigma_0}{E}(1 - e^{\frac{-t}{Trt}}) \qquad (3.27)$$

A linear model which goes a long way to simulate time-dependent behaviour of timber is the four element model- the Burgers model shown in Figure 3.4 (Dinwoodie, 1994). It consists of the Kelvin model put in series with a spring and a dashpot.

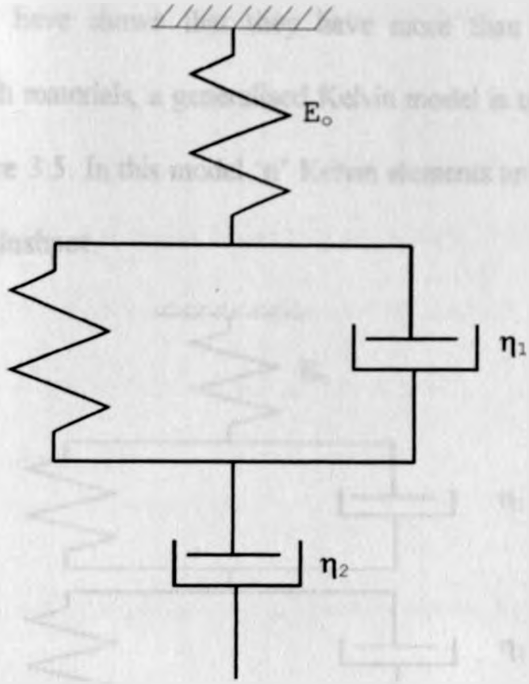

Figure 3.4. Burgers Model

The strain at any time, **t** under constant load for the model is given by the mathematical expression:

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{Er}(1 - e^{\frac{-t}{Tr}}) + \frac{\sigma_0 t}{\eta} \qquad (3.28)$$

Where **ε(t)** is strain at any time, $\mathbf{E_0}$ is the initial elasticity and $\mathbf{E_r}$ is retarded elasticity.

Creep compliance is defined as the ratio of strain to stress. From equation (3.28), creep compliance will be of the form:

$$J(t) = J_0 + J_r(1 - e^{\frac{-t}{Tr}}) + \frac{t}{\eta} \qquad (3.29)$$

Where $\mathbf{J_0}$ is initial compliance **(1/$\mathbf{E_0}$)** and $\mathbf{J_r}$ is retarded compliance **(1/$\mathbf{E_r}$)**

Most biological materials have shown that they have more than one retardation times (Mohsenin, 1970). For such materials, a generalised Kelvin model is used to predict its time-dependent behaviour, Figure 3.5. In this model 'n' Kelvin elements are connected in series to an initial spring and a final dashpot.

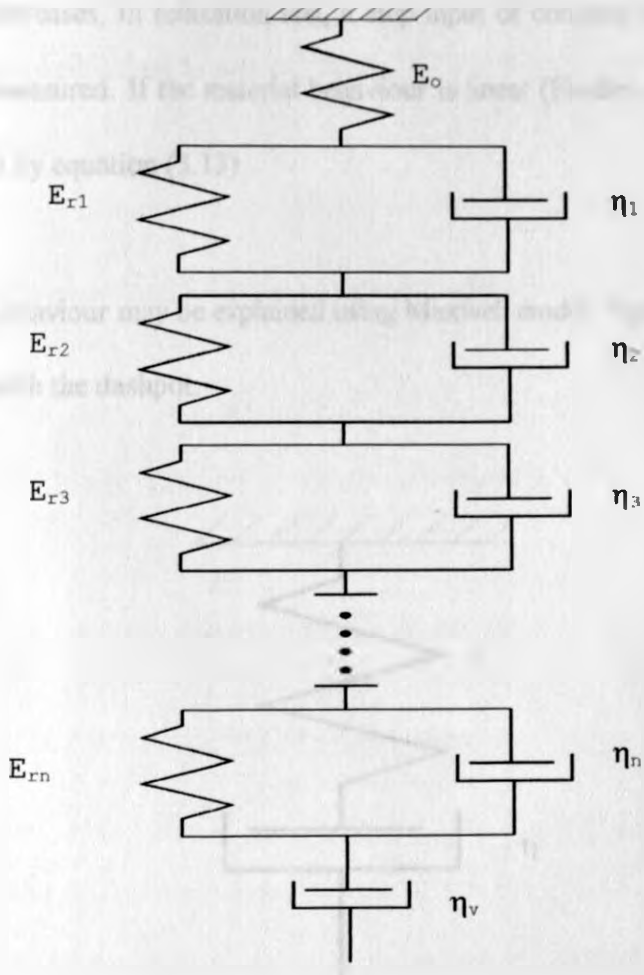

Figure 3.5. Generalised Kelvin Model

The mathematical expression for this model is similar to that of Burgers model and is of the form:

$$\varepsilon(t) = \sigma_0\{\frac{1}{E_0} + \frac{1}{E_{r1}}(1 - e^{\frac{-t}{T1}}) + \frac{1}{E_{r2}}(1 - e^{\frac{-t}{T2}}) + ... + \frac{1}{E_{rn}}(1 - e^{\frac{-t}{Tn}}) + \frac{t}{\eta_v}\} \qquad (3.30)$$

Where T_1, T_2,...T_n are different retardation times T_n, corresponding to various elements in the model.

This equation may be used to evaluate the creep compliance of timber

3.5.3 Stress Relaxation

Viscoelastic materials subject to a constant strain will relax under constant strain so that the stress gradually decreases. In relaxation test, a step input of constant strain ε_o is applied and the stress $\sigma(t)$ is measured. If the material behaviour is linear (Findley *et al*, 1976), the stress can be represented by equation (3.13)

Stress relaxation behaviour may be explained using Maxwell model, Figure 3.6. The model has a spring in series with the dashpot.

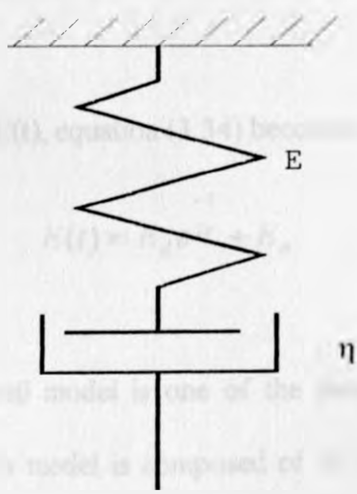

Figure 3.6. Maxwell Model

The strains in this model are additive. The governing equation is:

$$\varepsilon = \varepsilon_s + \varepsilon_v \tag{3.31}$$

Differentiating equation (3.31) and using equation (3.19) and (3.20), while noting that the stress is the same, we have;

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} \qquad (3.32)$$

For stress relaxation, the strain is constant, that is, $\dot{\varepsilon} = 0$, and replacing η/E by T_r we have,

$$0 = \dot{\sigma} + \frac{\sigma}{Tr} \qquad (3.33)$$

Where T_r is the relaxation time, a measure of time at which stress will be dissipated to 1/e of initial stress difference.

The above differential equation (3.33) can be solved to give

$$\sigma(t) = \sigma_d e^{\frac{-t}{Tr}} + \sigma_e \qquad (3.34)$$

Where σ(t) is stress at any time, σ_d is the decay stress (σ_o - σ_e) and σ_e is the stress at equilibrium.

In terms of relaxation modulus, E(t), equation (3.34) becomes

$$E(t) = E_d e^{\frac{-t}{Tr}} + E_e \qquad (3.35)$$

The generalised form of Maxwell model is one of the theories of linear viscoelasticity of materials (Mohsenin, 1970). This model is composed of 'n' Maxwell elements in parallel to Hookean element as in Figure 3.7. This model may be used to depict stress relaxation

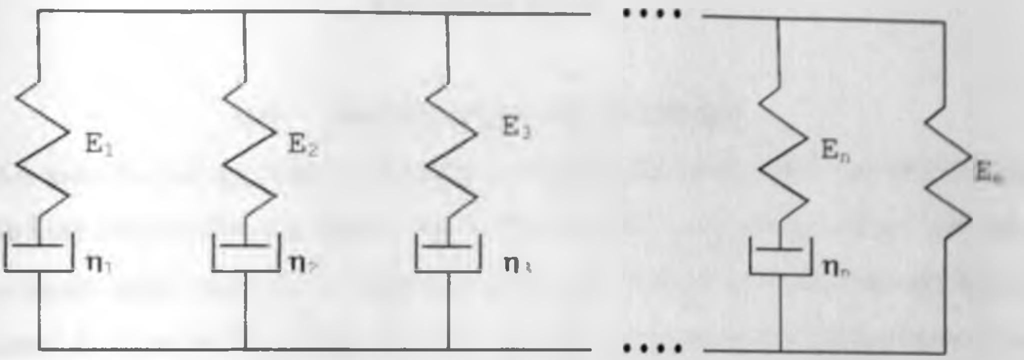

Figure 3.7. Generalised Maxwell Model

Under constant strain, at time **t** = 0, the total stress will be:

$$\sigma = \sigma_1 + \sigma_2 + \sigma_3 + \ldots + \sigma_n + \sigma_e \tag{3.36}$$

By superposition principle, the above equation (3.36) leads to;

$$\frac{\sigma(t)}{\varepsilon_0} = E_{d1}e^{\frac{-t}{T1}} + E_{d2}e^{\frac{-t}{T2}} + \ldots + E_{dn}e^{\frac{-t}{Tn}} + E_e \tag{3.37}$$

Where $\mathbf{T_1}$, $\mathbf{T_2}$ .....**Tn** are the relaxation times, $\mathbf{T_r}$ corresponding to various elements in the model.

Equation (3.37) may be used to give a mathematical expression for relaxation modulus.

CHAPTER FOUR

4.0 MATERIALS AND METHODS

Two Blue-gum trees of age thirty years and an average log diameter of 500 mm were obtained from the University of Nairobi, Kabete Farm. Two logs from each tree (3m long) were billet sawn to obtain timber sizes of 101.6 mm x 25.4 mm. The timbers were then naturally dried at Agricultural Engineering Workshop, until there was no moisture variation in and between the timbers. Test pieces were obtained from above timber sizes by sawing, followed planning to the required dimensions. The dimensions were measured by use of electronic Vernier callipers. The selection of the trees, logs and test specimens were done randomly, from their population respectively.

Tensile, compression and bending tests were carried out at Kenya Bureau of Standards (KBS). The three test were done using Torsee Universal Tensile Machine type AMU - 5 - DE, Figure 4.1. Creep and stress relaxation tests were carried out at Civil Engineering Timber Workshop, University of Nairobi.

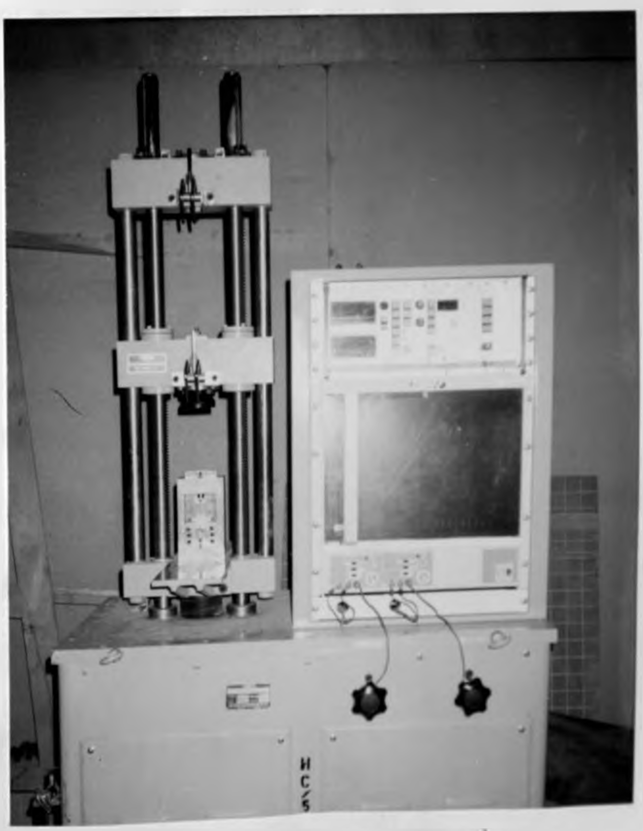

Figure 4.1. Universal Testing Machine

4.1 Moisture Determination

Moisture content determination was carried out based on BS 373:1957 with the assumption that Blue-gum timber has no volatile solids that can be lost during oven drying. Upon completion of each mechanical test, a sample was cut from a region where failure occurred for moisture content determination.

The sample mass (**M_1**) was determined and dried in oven at 105 °C till its mass was constant; upon which the final mass (**M_o**) was recorded. The percentage M.C (d.b) is:

$$(\frac{M_1 - M_0}{M_0})*100 \qquad (4.1)$$

4.2 Density

Thirty test pieces were used to determine the average density of the timber. The number of test was chosen to cater for inherent variability and that it is statistically sound (Tsoumis, 1994; and Steel and Torrie, 1980). The density ρ, of each test piece is the mass **m**, of the piece over its volume, **v**.

$$\rho = \frac{m}{v} \qquad (4.2)$$

4.3 Temperature and Relative Humidity

These were monitored for every specimen by use of two thermometers placed at one metre from the experiment set up and an hygrometer placed at the centre of testing room. The average value for each over the period of testing was taken as the temperature and relative humidity of property test.

4.4 Tensile and Compressive strength

Thirty tests for each were carried out based on BS 5820: 1969 and KS 02 - 982: 1990 (Part 3) The test pieces for tensile had the dimensions 220 mm x 15 mm x 10 mm, with minimum gauge length of 100 mm. For compression test the dimensions were 100 mm x 20 mm x 20 mm. Figures 4.2 and 4.3 shows the experiment set-up

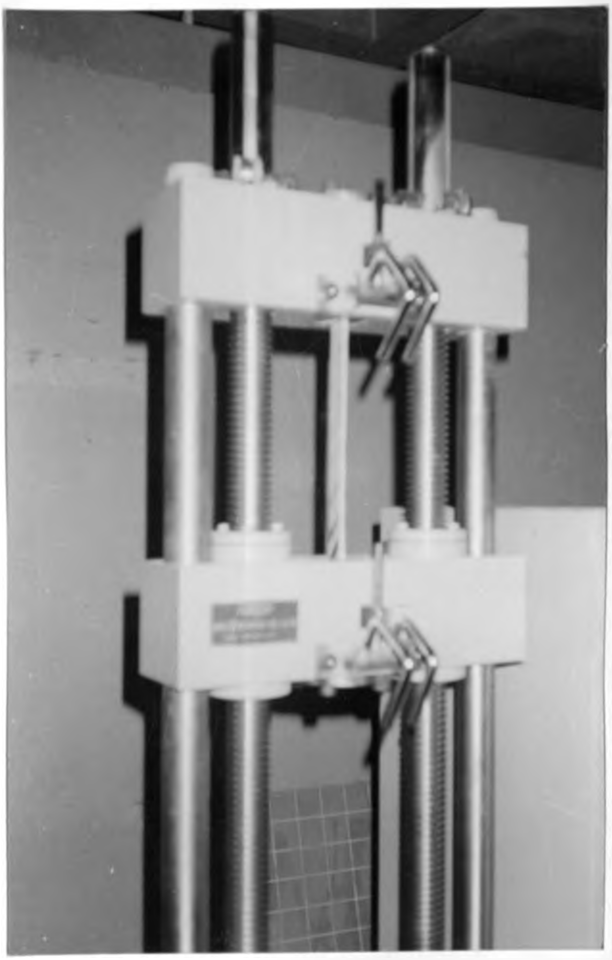

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Figure 4.2. Tensile Testing Set-up and Figure 4.3. Compression Testing Set-up

Tensile and compressive strength were obtained using the formula:

$$\sigma = \frac{F_{max}}{A} \tag{4.3}$$

Where σ is the tensile or compressive strength (Pa), F_{max} is the maximum load applied to attain failure (N) and **A** is the actual cross section are of specimen at test (m^2).

4.5 Bending strength

The standards followed and number of test is as in 4.4. The dimensions of bending test were 440 mm x 35 mm x 20 mm with minimum span length of 360 mm The experimental set-up is as shown in Figure 4.4

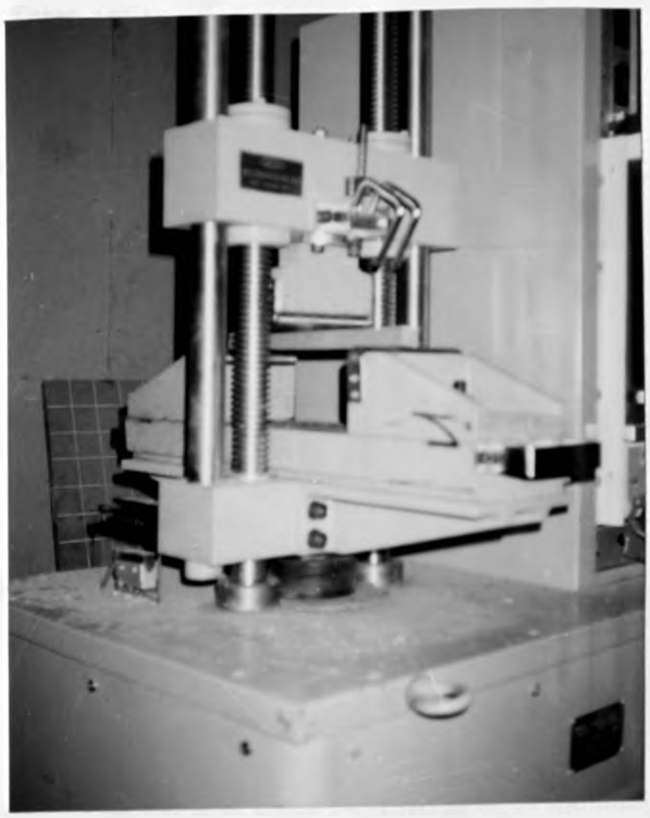

Figure 4.4. Bending Testing Set-up

The formula used for bending strength determination was:

$$\sigma_b = \frac{F_{max} L}{2Z} \qquad (4.4)$$

Where σ_b is the bending strength (Pa), F_{max} is the maximum load applied to attain failure (N), **L** is the distance from point of load application at neutral axis to support point (m) and **Z** is the section modulus (m^3)

Section modulus, **Z** was obtained from:

$$Z = \frac{I}{C} \qquad (4.5)$$

Where **C** is the maximum height from the neutral axis to point of load application (m) and **I** is the second moment of area, (m^4).

Second moment of area, **I** was obtained from:

$$I = \frac{bh^3}{12} \qquad (4.6)$$

Where **b** is the width of timber (m) and **h** is the height of the cross section of timber (m)

All measurements of timber were taken at test time.

4.6 Creep testing

Ten test were carried out, enough to give creep representation of the timber. The creep test set-up is as shown in Figure 4.5

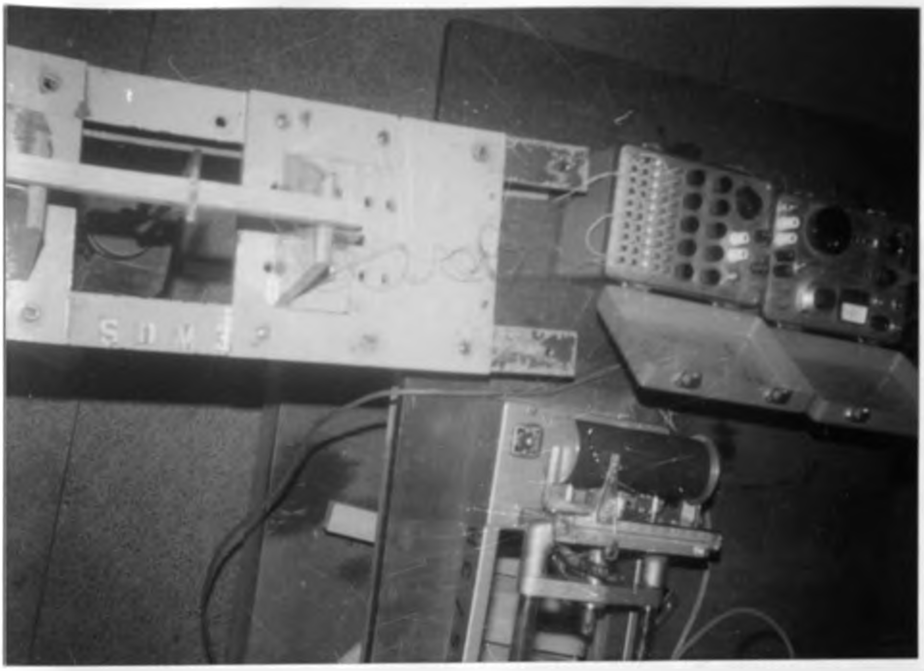

Figure 4.5. Creep and Stress Relaxation Set-up

The test load was applied without shock using a 3-point load system to the specimen of dimensions 300 mm x 20 mm x 20 with a span of 245 mm. Three incremental loads 542.8 N, 587.2 N and 646.1 N were applied at an interval of 5 seconds. The constant load applied of 646.1 N was the third. This load is a third of the ultimate load at bending test. The load is equivalent to the basic stress in design of timber in bending.

Strain gauges of 10 mm were attached at the centre of the span (Figure 4.6), where there is maximum straining.

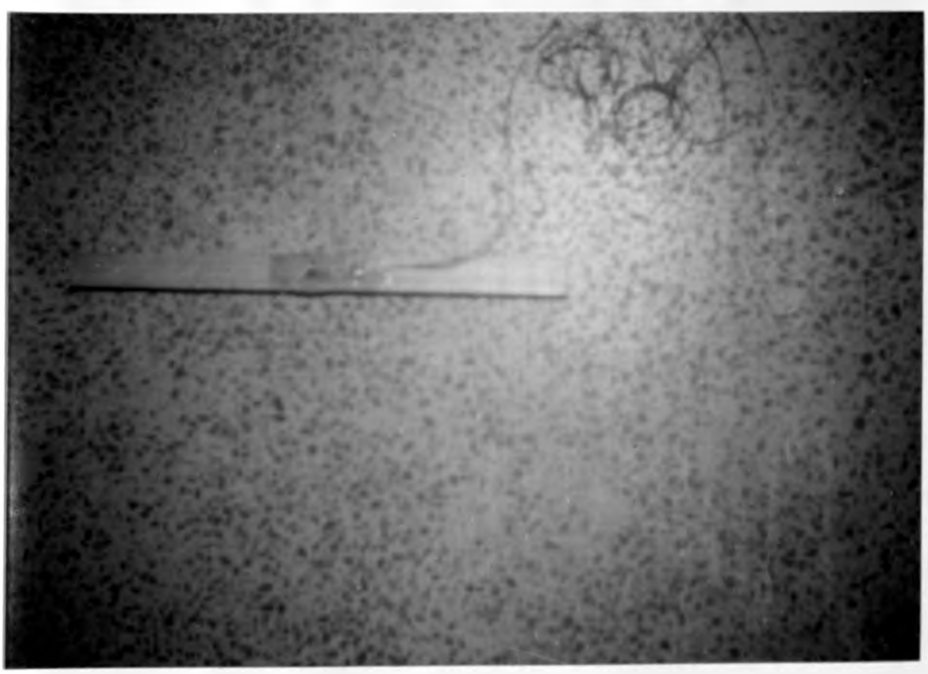

Figure 4.6. Strain Gauge attachment on Test piece.

Strain readings were taken at constant load at specified time intervals of; 5 minutes, 15 minutes and then 30 minutes for all subsequent readings. Thirteen strain readings were taken that satisfactorily depict creep response.

4.7 Stress Relaxation test

Experimental set-up, number of test and test pieces dimensions were as in 4.6 above. The maximum load applied was 646.1 N. The strain at this load was noted. This strain value was maintained by removing a load of 4.91 N while noting the time at which the test pieces had taken to dissipate off that load. Thirteen such loads were dissipated enough to draw a conclusive graph of stress relaxation. Strain gauges of 10 mm were attached as in 4.6 above.

4.8 Statistical Design.

Data collected for each mechanical test were analyzed using measures of central tendency and dispersion; the mean, standard deviation (S.D) and coefficient of variability (C.V) as outlined in Steel and Torrie (1980). For tensile, compression and bending results, a frequency distribution curve was plotted.

4.8.1 Samples and Sampling

Systematic sampling, such as application of American Standards has extensively been used in the past to determine the properties of various species, but now practically abandoned; current practice is sample at random from logs or lumber and according to the purpose of test (Dinwoodie, 1991).

Irrespective of the method of sampling, Wangaard (1950) contends that, sample size is an important criterion in assessing wood properties. Sample size depends on variation and is determined by statistical considerations.

CHAPTER FIVE

5.0 RESULTS AND DISCUSSION

5.1 Moisture Content

Moisture content plays a role in determining the strength properties of timber. It is one of the factors that determine strength property (Stamm, 1964). Strength increases with decrease in moisture content. Results of test for a particular timber can be compared when their moisture contents are known, usually with a mathematical expression relating strength and moisture content. The knowledge of this relationship of moisture to properties and processing ensures a rational use of timber.

The average moisture content of the timber specimens at test was 17%.

5.2 Density

The value of density in timber is the best indicator of strength (Lavers, 1969). In many instances it has be used to predict strength values of timber. It is positively correlated to strength: high density signifies high strength values, although this may not hold true for some woods. Density is not only important in predicting strength, but also as an index in quantitative production, an important aspect in industries which make products such as pulp, paper and fibreboard, as well as the production of wood in a forest. Density is a function of anatomical make-up of the wood, and the ratio of earlywood to latewood.

Density determination was done at moisture content of 17%. The average density at this moisture content was 963 kg/m^3. This value compares well with those of other related species *Eucalyptus Diversicolor* (938 kg/m^3), *Eucalyptus grandis* (705 kg/m^3), *Eucalyptus globulus* (880 kg/m^3) and *Eucalyptus camaldulensis* (910 kg/m^3) (TRADA, 1979)

5.3. Tensile Strength

Failure in tension is sudden, with little or no plastic deformation and occurs when the elastic limit of its fibre is exceeded (Lavers, 1969). Tensile strength depends on these fibres; their strength and orientation. The type of fracture is zigzag, Figure 5.1

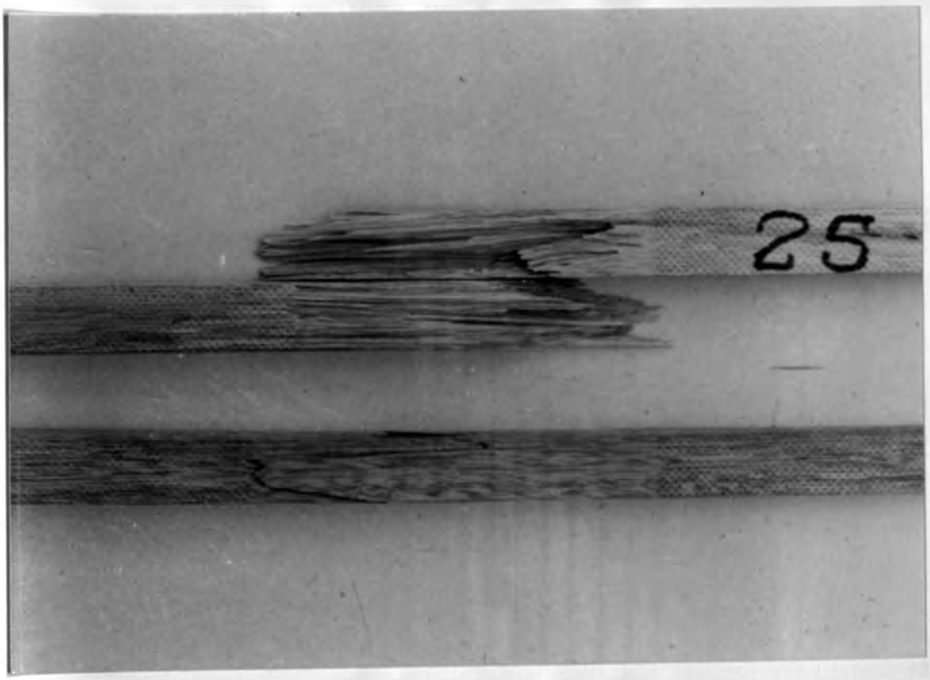

Figure 5.1 Failure Mode in Tension

The degree of interlocking is greater in latewood than earlywood (Mark, 1967), where the failure plane is vertical and a series of zigzag respectively. The author is convinced that failure in tension is through shear in fibre cells.

Tensile strength is the highest in Blue-gum. The average value for the thirty test undertaken was 123.0 MPa. The strength value was obtained at mean temperature of 23 °C and relative humidity of 63%

5.4 Compressive Strength

In timber, under compressive strength is provided for by lignin content. It gives the bondage to cells and thus acts as a stiffening agent. Failure in compression is gradual with a marked progress in development of structural change (Dinwoodie, 1978). The structural change resulting in deformation occurs in form of a kink in the microfibrils structure. This abnormal change leads to failure originating from the fibre walls being displaced vertically to accommodate horizontal running ray.

Continuous application of increasing load, increases these kinks till they become prominent, creating deformation lines. At failure, these deformation lines (creases) can be observed at the faces of the test piece, Figure 5.2.

Figure 5.2. Failure mode in Compression

Results of compression tests were obtained at 20.5 °C and relative humidity of 45%. Compressive strength in Blue-gum is about a third of tensile strength. The average value was 49.0 MPa.

5.5 Bending Strength

In bending, timber is subject to both compressive and tensile stress in the upper and lower part of the test piece respectively (Pearson, 1972). Bending failure occurs first on the compression side because compressive strength is nearly a third of tensile strength. The effect of the compressive force is to shift the neutral axis downwards from its central position, necessitating increase in cross-sectional area for applied load (force). The test piece fails when the tensile surface stresses reaches the ultimate bending strength, Figure 5.3 (a and b)

Figure 5.3 (a) Failure in Bending

Figue 5.3 (b) Failure in tension and compression sides under Bending load

The value obtained at failure for bending was 86.0 MPa at 20.5 °C and relative humidity of 45%. This value is about two-thirds of tensile strength.

A group frequency distribution for tensile, compressive and bending strengths is given in Figure 5.4.

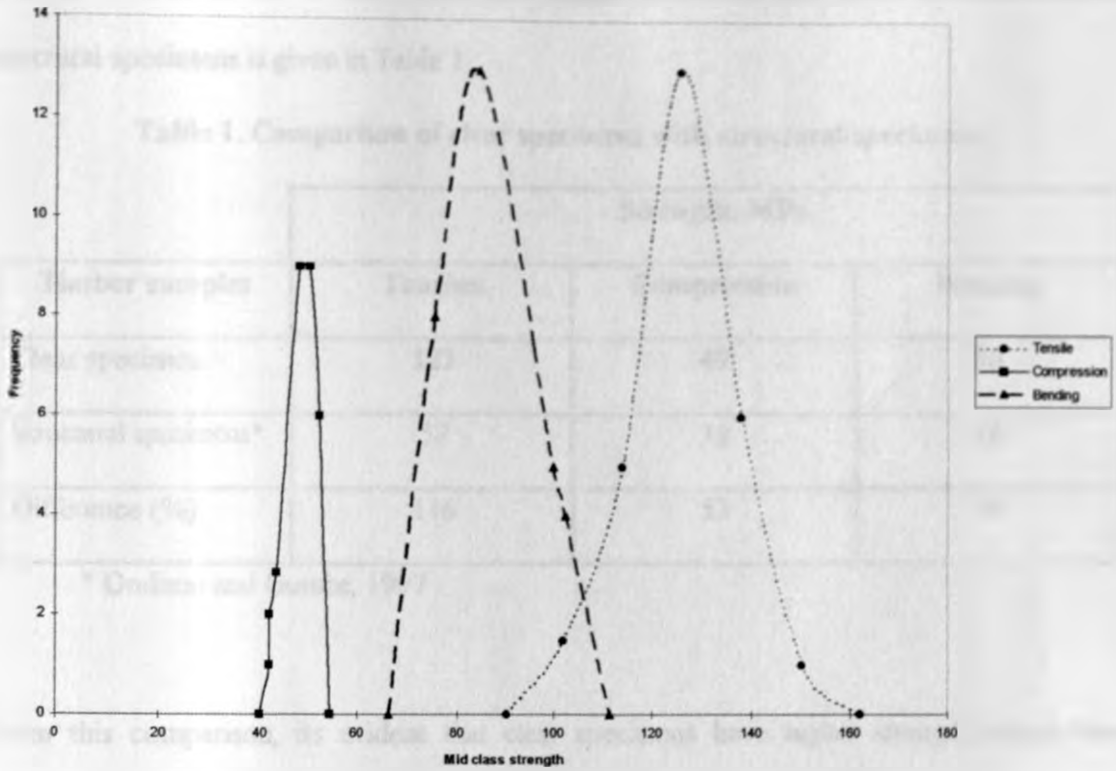

Figure 5.4. Frequency distribution of strength (MPa)

The tensile curve simulates the normal distribution curve. In effect, values obtained in this test had variations about the mean. A value of standard deviation (S.D) of 12.7 and co-efficient of variation (C.V) of 10.3

In contrast, the results of compressive strength, gave a narrow band indicating a small variations in values about the mean. The standard deviation and co-efficient of variation for compressive strength were 2.5 and 0.5 respectively. Bending strength values gave a skew (tilt) to the left. This indicates that values obtained below the mean value were many as compared to a few values above the mean. The standard deviation and co-efficient of variation were 9.0 and 1.1 respectively.

A comparison of the above three properties obtained from small clear specimens with those of structural specimens is given in Table 1

Table 1. Comparison of clear specimens with structural specimens

	Strength, MPa		
Timber samples	**Tension**	**Compression**	**Bending**
Clear specimen	123	49	86
Structural specimens*	57	32	48
Difference (%)	116	53	79

* Ondimu and Gumbe, 1997

From this comparison, its evident that clear specimens have higher strength values than structural specimens. This has been attributed to timber defects inherent in structural specimens.

For design purposes, values at above 1% confidence or a theoretical value above which 99% of the results fall, as well as the basic stresses are given in Table 2. Also given are values at maximum frequency.

Table 2 Values of above 99%, Basic stresses and Maximum frequency

Strength property, (MPa)	Above 99%	Basic stresses	Maximum frequency
Tensile	93.4	41.5	126.0
Compression	43.2	19.2	49.0
Bending	65.0	28.9	84.5

Table 3. Compares Blue-gum strengths with strengths of other timber sources found in Kenya timber markets

Table 3. Comparison of strengths of different timber types

	Strength, MPa		
Timber type	**Tension**	**Compression**	**Bending**
Blue-gum	123.0	49.0	86.0
Mahogany**	60.0	45.0	-
Teak**	118.0	65.0	-
Cypress*	-	37.8	68.0
Pine*	-	-	75.6

* Ondimu and Gumbe, 1997

** Tsoumis, 1991

The comparison shows that Blue-gum fares favourably well and that it can be the best structural material as timber is concerned, since it has the highest property strengths.

5.6. Creep Behaviour

Figure 5.5 represents the response of Blue-gum timber subject to a constant stress of 30 MPa and strains values were recorded for a period of 5.5 hours. The mean value of stress obtained for ten test carried were plotted against corresponding pre-set times

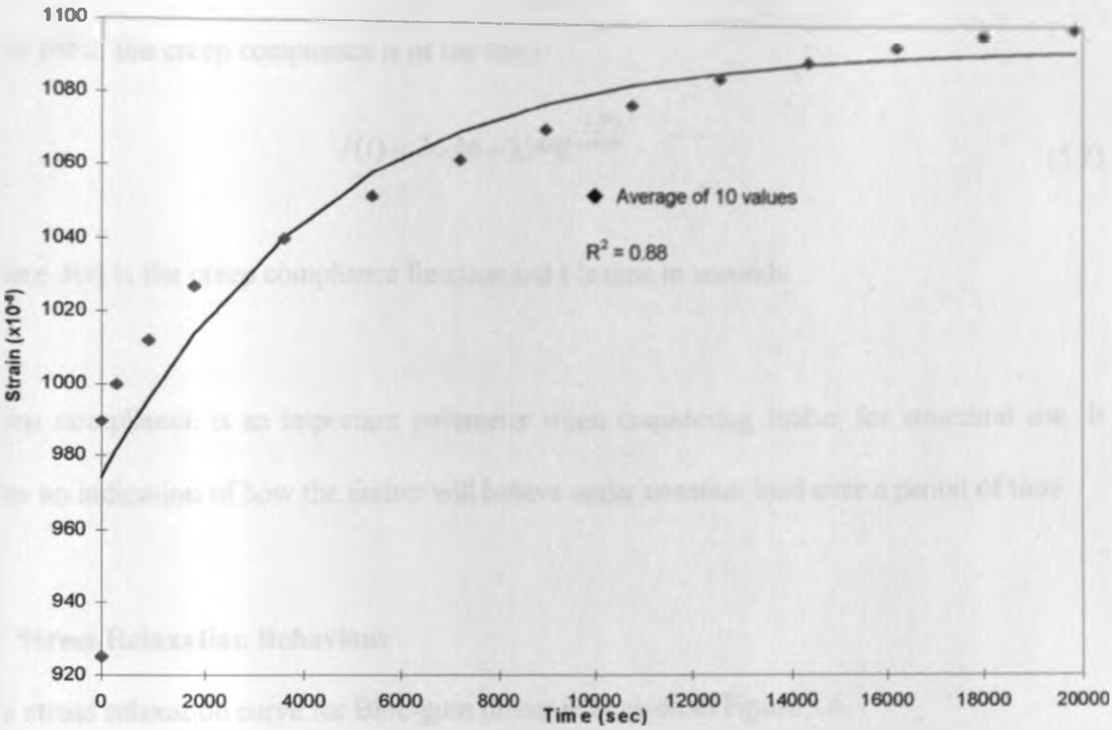

Figure 5.5. Creep response for Blue-gum.

For linear viscoelastic material (like timber at low stress value) obeying Boltzmann's principle of superposition, a series and parallel combination of springs and dashpots can be used to represent creep behaviour (Morlier and Palka, 1994).

The mathematical expression for creep obtained from the response curve using Genstat computer package (Appendix I) had the form:

$$\varepsilon(t) = 1093.9 - 119.8e^{\frac{-2.24t}{10000}} \tag{5.1}$$

Where $\varepsilon(t)$ is the creep function at any time and t the time

This equation is similar to equation (3.27) for Kelvin model

By definition, creep compliance is the ratio of strain to stress. Therefore for the constant load of 30 MPa, the creep compliance is of the form:

$$J(t) = 36.46 - 3.99e^{\frac{-2.24t}{10000}} \qquad (5.2)$$

Where **J(t)** is the creep compliance function and t is time in seconds.

Creep compliance is an important parameter when considering timber for structural use. It gives an indication of how the timber will behave under constant load over a period of time.

5.7 Stress Relaxation Behaviour

The stress relaxation curve for Blue-gum timber is as given in Figure 5.6.

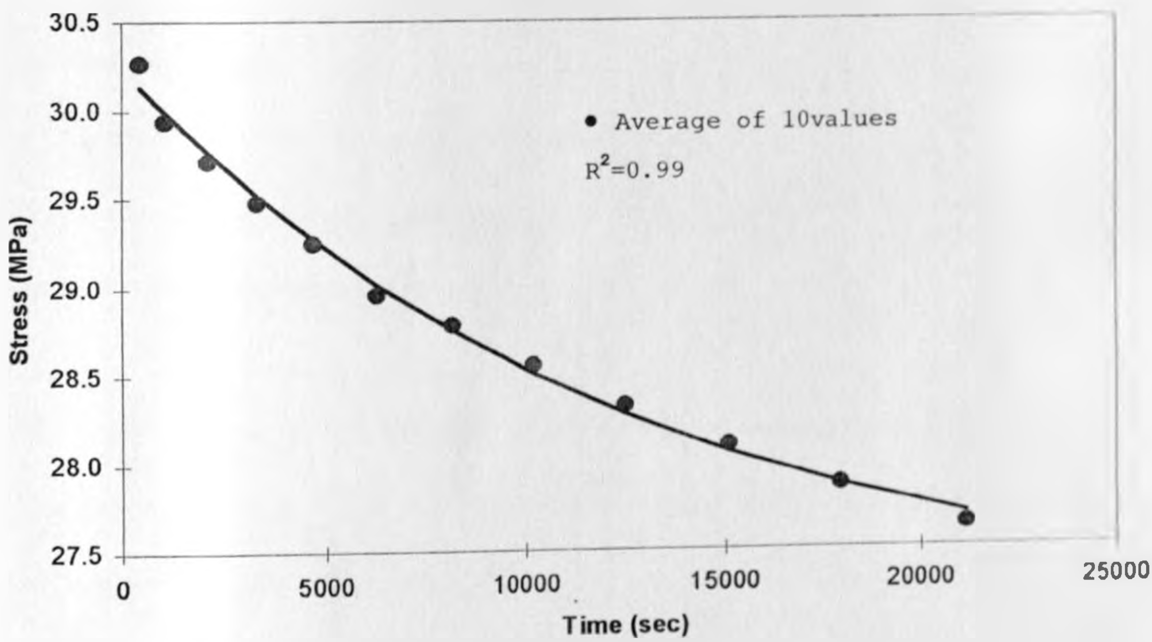

Figure 5.6. Stress Relaxation Response for Blue-gum.

The expression obtained for stress relaxation modulus from the curve using Genstat computer package (Appendix J) is of the form

$$E(t) = 27.048 + 3.183e^{\frac{-7.91t}{10000}} \text{ MPa} \tag{5.3}$$

The modulus explains the stiffness of the timber and can be used to predict the amount of stress the timber will dissipate over time in its structural position. At a stress of 30 MPa, which timbers are normally subjected, the stress-strain behaviour is linearly viscoelastic.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions can be made within the range of this study

(a) At 17% moisture content, the average density is 963 kg/m^3 and the strength values are; tension 123 MPa, compression 49 MPa and in bending 86 MPa,

(b) The expression for creep and stress relaxation can be modelled as linearly viscoelastic material at a basic stress value of 30 MPa; this being a third of bending strength;

(c) Clear elements had the highest strength as compared to structural elements. The difference being highest in tension; and

(d) The timber had higher strength properties than most timber sources in Kenya

6.2 Recommendations

The following recommendations can be made from the study:

1. Due to the variability of timber strengths arising from growth environment of wood, there is need to develop a relationship linking these variations; and

2. The viscoelastic behaviour of Blue-gum timber need to be analysed under different stress value, different loading modes (tension, compression and shear) and in an environment which the timber is subjected when in use.

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APPENDICES

A. Tensile Test Values

Specimen	b (mm)	w (mm)	Area (x 10^{-4} m^2)	M.C (%)	F_{max} (kN)	Stress (MPa)
1	9.47	14.28	1.352	17.00	17.876	132.222
2	9.72	13.70	1.332	17.26	16.306	122.417
3	9.22	13.80	1.272	16.50	16.350	128.538
4	9.87	14.31	1.412	16.36	18.203	128.538
5	9.75	13.78	1.344	16.97	16.786	124.896
6	9.86	14.57	1.437	18.45	19.184	133.500
7	9.94	14.22	1.413	17.44	17.440	123.425
8	9.48	14.02	1.329	16.16	16.394	123.336
9	9.79	13.83	1.354	18.41	13.560	100.148
10	9.55	13.63	1.302	17.39	12.862	98.786
11	9.87	14.40	1.421	16.58	20.274	142.674
12	9.62	14.51	1.396	17.51	20.601	147.572
13	9.36	13.29	1.244	18.19	15.696	126.174
14	9.73	14.31	1.392	17.03	16.677	119.806
15	9.60	13.40	1.286	16.85	14.933	116.120
16	9.36	13.22	1.237	16.94	17.004	137.462
17	9.26	14.18	1.313	16.73	16.350	124.524
18	9.07	13.05	1.184	16.82	16.023	135.329
19	9.29	14.16	1.315	18.14	17.004	129.308
20	9.67	14.51	1.403	18.47	17.004	121.197
21	9.76	14.55	1.420	16.35	19.838	139.704
22	9.99	14.34	1.433	15.87	16.786	117.139
23	9.72	14.89	1.447	16.46	15.260	105.460
24	9.91	14.63	1.450	16.33	16.895	116.517
25	9.96	14.77	1.471	16.75	17.004	115.595
26	9.80	14.14	1.381	16.53	14.170	102.606
27	10.21	14.64	1.495	17.12	18.966	126.863
28	9.99	14.15	1.414	16.94	13.734	97.129
29	9.96	14.11	1.405	16.64	17.113	121.801
30	9.87	14.18	1.400	16.49	17.658	126.129
			Average	17.02		122.843
			Standard Deviation	0.71		12.686
			Co-eff. of variation	4.17		10.327

Mean Temperature: 23°C   Mean Relative Humidity: 63

B. Compression Test Values

Specimen	b (mm)	w (mm)	Area (x 10^{-4} m^2)	M.C (%)	F_{max} (kN)	Stress (MPa)
1	20.7	21.2	4.39	17.01	21.42	48.79
2	21.1	20.5	4.33	17.10	19.29	44.55
3	20.6	20.6	4.24	18.32	21.75	51.30
4	20.8	20.7	4.31	17.22	20.76	48.17
5	20.4	20.7	4.22	17.68	21.75	51.54
6	20.2	20.1	4.06	18.17	20.93	51.55
7	21.0	20.7	4.35	18.05	22.04	50.67
8	20.1	20.3	4.08	16.96	19.62	48.09
9	20.6	20.5	4.22	16.92	20.67	48.98
10	20.1	21.0	4.22	17.23	19.59	46.42
11	21.6	20.5	4.43	17.56	19.62	44.29
12	20.9	20.0	4.18	17.07	17.49	41.84
13	20.1	20.3	4.08	17.15	19.95	48.90
14	21.1	21.0	4.43	17.25	21.58	48.71
15	20.5	21.9	4.49	16.67	21.09	46.97
16	20.5	20.5	4.20	18.72	22.01	52.40
17	20.2	20.1	4.06	17.78	20.47	50.42
18	20.4	20.4	4.16	18.47	21.91	52.67
19	20.6	21.1	4.35	17.29	21.09	48.48
20	22.0	20.6	4.53	17.36	22.56	49.80
21	20.7	20.3	4.20	17.25	20.99	49.98
22	21.3	20.7	4.41	17.41	22.01	49.91
23	20.7	20.0	4.14	17.13	20.27	48.96
24	20.5	20.7	4.24	17.34	21.26	50.14
25	20.5	20.8	4.26	17.43	21.61	50.73
26	20.0	21.1	4.22	18.09	21.06	49.91
27	20.8	20.8	4.33	17.33	20.31	46.91
28	21.8	20.8	4.53	17.84	22.89	50.53
29	20.6	20.9	4.31	18.19	22.07	51.21
30	20.5	20.9	4.28	17.38	20.60	48.13
			Average	17.51		49.03
			Standard Deviation	0.51		2.45
			Co-eff. Of Variation	2.91		0.50

Mean Temperature: 20.5°C

Mean Relative Humidity: 45

C. Bending Test Values

Specimen	l (10^{-3} m)	b (10^{-3} m)	h (10^{-3} m)	I (10^{-9} m^4)	Z (10^{-6} m^3)	M.C (%)	F_{max} (kN)	Stress (MPa)
1	180	33.1	19.1	19.220	2.012	16.98	1.921	85.929
2		35.2	20.0	23.467	2.347	16.31	1.896	72.706
3		34.2	19.5	21.132	2.167	16.18	1.742	72.349
4		34.3	19.7	21.853	2.219	17.14	2.071	83.997
5		35.6	20.2	24.452	2.421	17.36	2.06	76.580
6		34.2	19.3	20.489	2.123	18.08	2.289	97.037
7		35.0	20.0	23.333	2.333	16.71	2.284	88.110
8		34.0	19.6	21.334	2.177	16.86	1.891	78.176
9		34.3	19.4	20.870	2.152	17.48	1.989	83.183
10		34.2	19.6	21.459	2.190	16.78	1.957	80.425
11		35.3	19.4	23.888	2.275	16.28	1.973	78.053
12		35.2	19.6	25.643	2.490	18.41	2.469	89.241
13		34.5	20.1	22.317	2.254	16.02	1.788	71.393
14		34.3	20.6	19.297	2.042	17.61	1.733	76.381
15		35.0	19.8	21.961	2.241	17.45	2.507	100.683
16		34.7	18.9	20.467	2.132	18.50	2.365	99.836
17		34.2	19.6	20.809	2.145	17.25	2.006	84.168
18		34.7	19.2	22.446	2.267	17.97	2.453	80.941
19		34.7	19.4	25.278	2.454	16.55	2.207	97.384
20		34.5	19.8	22.317	2.254	17.04	2.502	99.902
21		34.3	19.8	22.187	2.241	18.33	2.474	99.357
22		34.2	19.8	22.123	2.235	17.89	2.371	95.477
23		34.4	19.4	20.931	2.158	16.98	2.071	86.372
24		34.8	20.4	24.620	2.414	17.47	2.333	86.980
25		34.2	19.8	22.123	2.235	16.35	1.853	74.617
26		35.6	20.1	24.091	2.397	17.59	2.235	83.917
27		34.3	19.8	22.188	2.241	16.70	2.017	81.004
28		34.1	19.5	21.071	2.161	17.27	2.093	87.168
29		35.1	19.9	23.051	2.317	17.07	2.196	85.300
30	180	34.3	19.6	21.522	2.196	17.31	2.371	97.172
					Average	17.20		85.795
					Std. Deviat.	0.67		9.048
					Co-eff. Var.	3.90		1.055

Mean Temperature: 20.5°C

Mean Relative Humidity: 45

D. Density Determination Values

Specimen	l (10^{-3} m)	b (10^{-3} m)	w (10^{-3} m)	Volume (10^{-6} m^3)	Mass (10^{-2} kg)	Density (kg/m^3)
1	43.2	19.7	32.2	2.740	2.728	995.62
2	42.4	19.4	34.8	2.863	2.682	936.78
3	43.0	19.4	33.8	2.820	2.801	993.26
4	43.9	19.6	35.2	3.287	3.134	923.03
5	42.8	19.8	34.7	2.941	2.840	965.66
6	42.0	19.8	33.9	2.819	2.756	977.65
7	42.8	19.5	34.8	2.904	2.850	981.40
8	43.3	19.2	33.4	2.777	2.620	943.46
9	42.3	19.1	33.8	2.731	2.614	957.16
10	42.0	19.0	33.2	2.649	2.575	972.06
11	42.0	19.5	34.9	2.858	2.650	927.22
12	43.5	20.0	34.5	3.002	2.985	994.34
13	44.4	19.6	34.4	2.994	2.897	967.60
14	42.5	18.9	33.0	2.651	2.451	924.56
15	42.5	19.4	34.6	2.853	2.618	917.63
16	44.9	20.4	34.6	3.169	3.106	980.12
17	40.9	18.7	33.9	2.593	2.583	996.14
18	42.4	19.8	34.6	2.905	2.889	994.49
19	42.5	20.0	34.7	2.950	2.824	957.29
20	42.8	19.6	34.4	2.886	2.864	992.38
21	42.4	19.6	34.8	2.892	2.885	997.58
22	43.4	19.4	35.0	2.947	2.919	990.50
23	41.2	18.9	33.6	2.616	2.556	997.06
24	44.2	19.6	34.6	2.997	2.837	946.61
25	42.7	19.2	34.0	2.787	2.669	957.66
26	43.8	20.4	35.2	3.145	3.068	975.52
27	41.8	19.0	33.5	2.661	2.543	955.66
28	40.6	19.9	32.8	2.650	2.438	920.00
29	41.2	19.6	34.8	2.810	2.558	910.32
30	42.3	19.6	34.0	2.819	2.656	942.18
					Average	963.03
					Std Deviation	28.22
					Co-eff. Var.	2.93

E (i). Creep Test (Time & Strains Values)

Stress (MPa)	Time (Secs.)	Strain Reading per specimen (x 10^{-6})										Average
		1	2	3	4	5	6	7	8	9	10	Strain
25.203		1072	860	738	758	720	905	916	796	796	749	851
27.264	5	1166	926	798	1033	750	983	1100	859	843	793	925
30.000	10	1255	994	858	1106	790	1057	1181	923	896	842	990
	300	1265	1001	864	1116	808	1064	1191	930	907	853	1000
	900	1274	1010	872	1131	824	1074	1212	943	919	864	1012
	1800	1284	1028	888	1147	838	1085	1132	956	934	878	1027
	3600	1293	1045	903	1160	850	1095	1150	968	947	890	1040
	5400	1301	1060	916	1172	860	1104	1166	978	959	900	1052
	7200	1309	1074	928	1181	869	1112	1280	986	969	908	1062
	9000	1316	1082	939	1199	877	1119	1292	993	977	915	1071
	10800	1322	1091	949	1206	884	1125	1302	999	984	921	1078
	12600	1327	1100	958	1211	890	1130	1310	1004	990	926	1085
	14400	1331	1108	966	1215	895	1134	1316	1008	995	930	1090
	16200	1334	1114	973	1219	899	1137	1320	1011	999	933	1094
	18000	1336	1119	979	1222	902	1139	1322	1013	1003	935	1097
	19800	1337	1122	982	1224	904	1140	1323	1014	1006	936	1099

Mean Temperature: 19°C

Mean Relative Humidity: 45

E (ii). Creep Test (Stresses per Specimen)

Specimen	l (x 10^{-3} m)	b (x 10^{-3} m)	h (x 10^{-3} m)	I (x 10^{-9} m^4)	Z (x 10^{-6} m^3)	M.C (%)	Stress (MPa) at Loading:		
							542.8 N	587.2 N	646.1 N
1	122.5	19.8	19.90	13.003	1.306	15.70	25.457	27.539	30.301
2		20.2	19.90	13.266	1.333	16.61	24.941	26.981	29.688
3		19.8	20.00	13.200	1.320	16.61	25.187	27.247	29.980
4		20.4	19.70	12.997	1.320	15.65	25.187	27.247	29.980
5		19.8	19.80	12.808	1.294	15.27	25.693	27.247	30.582
6		19.8	19.90	13.003	1.307	15.18	25.437	27.794	30.278
7		20.1	19.90	13.200	1.327	16.13	25.054	27.518	29.822
8		19.8	20.10	13.399	1.333	15.06	24.941	27.103	29.688
9		20.2	19.90	13.266	1.333	15.38	24.941	26.981	29.688
10		20.0	19.90	13.134	1.320	15.60	25.187	27.247	29.980
					Average	15.72	25.203	27.264	30.000
					Std. Deviation	0.56	0.256	.277	.304
					Co-eff. Var.	3.56	1.014	1.014	1.013

F (i). Relaxation Test (Time & Stresses Values)

Strain (x 10^{-6})	Stress (MPa)	Time Readings per specimen (mins.)										Average
		1	2	3	4	5	6	7	8	9	10	(Secs)
1227	30.403											
	30.269	4	8	8	7	5	6	7	8	11	4	408
	29.942	13	19	21	16	15	16	18	17	25	9	1014
	29.714	32	39	36	28	35	45	36	31	41	19	2052
	29.481	56	62	53	42	57	76	57	47	63	32	3270
	29.250	81	88	74	59	80	111	81	65	90	47	4656
	28.960	109	116	98	79	115	151	109	85	120	64	6276
	28.789	145	146	125	102	152	196	141	108	154	84	8118
	28.558	185	179	156	129	194	246	179	134	192	106	10200
	28.328	228	216	191	159	238	301	222	164	235	131	12510
	28.097	273	257	232	192	286	362	270	199	284	159	15090
	27.867	321	303	281	228	340	428	323	240	338	190	17952
	27.631	373	354	339	268	402	500	381	288	399	225	21174

Mean Temperature: 20°C

Mean Relative Humidity: 46

F (ii). Relaxation Test (Load & Stresses Values)

Load (N)	Specimen Stress (MPa)										Average
	1	2	3	4	5	6	7	8	9	10	Stress
646.1	31.383	29.98	29.533	31.209	30.749	29.098	30.14	30.749	29.98	31.209	30.403
641.2	31.145	29.753	29.309	30.973	30.997	28.878	29.911	30.997	29.753	30.973	30.269
636.3	30.906	29.525	29.085	30.736	30.282	28.657	29.683	30.282	29.525	30.736	29.942
631.4	30.669	29.298	28.861	30.499	30.049	28.436	29.454	30.049	29.298	30.499	29.714
626.5	30.431	29.071	28.637	30.263	29.816	28.216	29.226	29.816	29.071	30.263	29.481
621.6	30.193	28.843	28.413	30.026	29.583	27.995	28.997	29.583	28.843	30.026	29.250
616.7	29.955	28.616	28.189	29.789	29.350	27.774	28.768	29.35	28.616	29.189	28.960
611.8	29.717	28.388	27.965	29.553	29.116	27.553	28.540	29.116	28.388	29.553	28.789
606.9	29.479	28.161	27.741	29.316	28.883	27.333	28.311	28.883	28.161	29.316	28.558
602.0	29.241	27.934	27.517	29.079	28.650	27.112	28.083	28.65	27.934	29.079	28.328
597.1	29.003	27.706	27.293	28.843	28.417	26.891	27.854	28.417	27.706	28.843	28.097
592.2	28.765	27.479	27.069	28.606	28.184	26.671	27.625	28.184	27.479	28.606	27.867
587.2	28.522	27.247	26.840	28.364	27.946	27.392	27.392	27.946	27.247	28.364	27.631

Specimen Strain (x 10^{-6})										
1350	1280	1270	1080	1394	1320	840	1250	828	1658	1227.000
									Std. Dev.	252.360
									Co-eff. Var	20.570

Specimen M.C (%)										
15.51	15.87	16.85	15.05	15.03	15.92	15.88	15.23	15.09	15.43	15.59
									Std. Dev.	0.57
									Co-eff. Var	3.66

F (iii). Stress Relaxation Dimensions

Specimen	Dimensions			
	l (x10^{-2}m)	b (x 10^{-3})	h (x 10^{-3} m)	Z (x 10^{-6} m^{3})
1	12.25	19.7	19.6	1.261
2		19.8	20.0	1.320
3		19.9	20.1	1.340
4		19.6	19.7	1.268
5		19.7	19.8	1.287
6		20.2	20.1	1.360
7		19.9	19.9	1.313
8		19.7	19.8	1.287
9		20.2	19.8	1.320
10		19.8	19.6	1.268

G. Moisture Determination Values

Specimen	Tensile		Compression		Bending		Creep		Relaxation	
	Ww	Wd	Ww	Wd	Ww	Wd	Ww	Wd	Ww	Wd
1	30.44	26.04	24.14	20.63	27.28	23.32	39.80	34.40	40.95	35.45
2	30.10	25.67	24.79	21.17	26.82	23.06	40.70	34.90	38.70	33.40
3	31.49	27.03	26.74	22.60	28.01	24.11	34.40	29.50	41.95	35.90
4	32.14	27.62	25.39	21.66	30.34	25.90	38.80	33.55	36.70	31.90
5	30.74	26.28	27.42	23.30	28.40	24.20	38.50	33.40	36.35	31.60
6	31.13	26.28	27.45	23.23	27.56	23.34	42.50	36.90	42.60	36.75
7	30.84	26.26	26.55	22.49	28.50	24.42	32.40	27.90	41.95	36.20
8	16.39	14.11	24.76	21.17	26.20	22.42	46.60	40.50	37.45	32.50
9	30.42	25.79	23.77	20.33	26.14	22.25	45.00	39.00	40.80	35.45
10	29.56	25.18	24.49	20.89	25.75	22.05	37.80	32.70	36.65	31.75
11	30.23	25.93	28.25	24.03	26.50	22.79				
12	32.01	27.24	23.46	20.04	29.85	25.21				
13	27.29	23.09	25.20	21.51	28.97	24.97				
14	31.00	26.49	26.78	22.84	24.51	20.84				
15	29.27	25.05	25.69	22.02	26.18	22.29				
16	28.02	23.96	27.27	22.97	31.06	26.21				
17	31.05	26.60	24.77	21.03	25.83	22.03				
18	26.18	22.41	26.88	22.69	28.89	24.49				
19	31.26	26.46	26.86	22.90	28.24	24.23				
20	32.46	27.40	27.92	23.79	28.64	24.47				
21	30.96	26.61	25.69	21.91	28.85	24.38				
22	30.30	26.15	28.05	23.89	29.19	24.76				
23	27.52	23.63	26.26	22.42	25.56	21.85				
24	26.99	23.20	27.21	23.19	28.37	24.15				
25	28.30	24.24	27.42	23.35	26.69	22.94				
26	26.08	22.38	25.72	21.78	30.68	26.09				
27	28.73	24.53	25.79	21.98	25.43	21.79				
28	26.02	22.25	28.20	23.93	24.38	20.79				
29	26.92	23.08	27.16	22.98	25.58	21.85				
30	26.63	22.86	24.85	21.17	26.56	22.64				

H: Statistical Analysis Formulae.

(a) The Mean

$$\bar{X} = \frac{\sum_{i}^{n} X_i}{n}$$

Where **X** is observed value and **n** is the number of observation

(b) The Standard Deviation (S. D)

$$S.D = \sqrt{\frac{\sum_{i}^{n} X_i^2 - \frac{(\Sigma X_i)^2}{n}}{n}}$$

(c) The co-effient of variation

$$C.V = \frac{100S.D}{\bar{X}}$$

(d) The Theoretical Value above which 99% of the results fall

$$\sigma_t = \bar{X} - 2.33S.D$$

(e) Basic. Stress

$$\sigma_b = \frac{\bar{X} - 2.33S.D}{2.25}$$

I: Creep Curve Analysis

Nonlinear regression analysis

Response variate: Strain
Explanatory: Time
Fitted Curve: A + B*R**X
Constraints: R < 1

*** Summary of analysis ***

	d.f.	s.s.	m.s	v.r	F pr
Regression	2	30801.	15400.5	50.10	<.001
Residual	12	3689.	307.4		
Total	14	34490.	2463.6		
Change	2	-30801.	-15400.5	-50.10	<.001

Percentage variance accounted for 87.5
Standard error of observations is estimated to be 17.5
* MESSAGE: The following units have large standardized residuals:
1 -3.38
* MESSAGE: The residuals do not appear to be random;
for example, fitted values in the range 1040.5 to 1086.8
are consistently larger than observed values
and fitted values in the range 974.4 to 1014.0
are consistently smaller than observed values

*** Estimates of parameters ***

	estimate	s.e.
R	0.9997756	0.0000735
B	-119.8	12.4
A	1093.9	10.2

*** Correlations between parameter estimates ***

estimate	ref	correlations		
R	1	1.000		
B	2	-0.276	1.000	
A	3	0.778	-0.644	1.000
		1	2	3

*** Fitted values and residuals ***

Unit	Explanatory	Response	Fitted value	Standardized residual	Leverage
1	5.0000	925.0	974.3	-3.38	0.31
2	10.0000	990.0	974.4	1.07	0.31
3	300.0000	1000.0	981.9	1.17	0.23
4	900.0000	1012.0	996.1	0.99	0.16
5	1800.0000	1027.0	1014.0	0.82	0.18
6	3600.0000	1040.0	1040.5	-0.04	0.26
7	5400.0000	1052.0	1058.3	-0.41	0.24
8	7200.0000	1062.0	1070.1	-0.51	0.17
9	9000.0000	1071.0	1078.0	-0.43	0.13
10	10800.0000	1078.0	1083.3	-0.32	0.11
11	12600.0000	1085.0	1086.8	-0.11	0.12
12	14400.0000	1090.0	1089.2	0.05	0.15
13	16200.0000	1094.0	1090.8	0.20	0.18
14	18000.0000	1097.0	1091.8	0.33	0.21
15	19800.0000	1099.0	1092.5	0.43	0.24
Mean	8001.0000	1048.1	1048.1	-0.01	0.20

J: Stress Relaxation Curve Analysis

***** Nonlinear regression analysis *****

Response variate: Strain
Explanatory: Time
Fitted Curve: A + B*R**X
Constraints: R < 1

*** Summary of analysis ***

	d.f.	s.s.	m.s.	v.r.	F pr
Regression	2	7.82682	3.913410	939.90	<.001
Residual	9	0.03747	0.004164		
Total	11	7.86429	0.714936		
Change	2	-7.82682	-3.913410	-939.90	<.001

Percentage variance accounted for 99 4
Standard error of observations is estimated to be 0 0645
* MESSAGE: The following units have large standardized residuals
1 2.78
* MESSAGE: The following units have high leverage
12 0.56

*** Estimates of parameters ***

	estimate	s.e
R	0.99992426	0.00000906
B	3.183	0.173
A	27.048	0.195

*** Correlations between parameter estimates ***

estimate	ref	correlations		
R	1	1.000		
B	2	0.906	1.000	
A	3	-0.971	-0.973	1.000
		1	2	3

*** Fitted values and residuals ***

Unit	Explanatory	Response	Fitted value	Standardized residual	Leverage
1	408.0000	30.2690	30.1341	2.78	0 43
2	1014.0000	29.9420	29.9956	-0.99	0 30
3	2052.0000	29.7140	29.7727	-1.01	0.18
4	3270.0000	29.4810	29.5326	-0.86	0 15
5	4656.0000	29.2500	29.2849	-0.59	0 16
6	6576.0000	28.9600	28.9821	-0.38	0 20
7	8118.0000	28.7890	28.7689	0.35	0 21
8	10200.0000	28.5580	28.5178	0.69	0.19
9	12510.0000	28.3280	28.2818	0.78	0.17
10	15090.0000	28.0970	28.0627	0.58	0 17
11	17952.0000	27.8670	27.8649	0.04	0 28
12	21174.0000	27.6310	27.6879	-1.33	0 56
Mean	8585.0000	28.9072	28.9072	0.00	0 25