INVESTIGATION OF CREEP BEHAVIOUR OF BLACK AFARA (*Terminalia ivorensis*) TIMBER

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DEPARTMENT OF CIVIL ENGINEERING
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MARCH, 2017.

DECLARATION

I hereby declare that this Thesis entitled **''Investigation of Creep Behaviour of Black Afara (*Terminalia ivorensis*) Timber''** was carried out by me in the Department of Civil Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

Amodu Ismaila MOHAMMED

Name of Student	Signature	Date

CERTIFICATION

This Thesis entitled **''INVESTIGATION OF CREEP BEHAVIOUR OF BLACK AFARA (*Terminalia ivorensis*) TIMBER''** by Amodu Ismaila MOHAMMED, meets the regulations governing the award of degree of Doctor of Philosophy in Civil Engineering Department of the Ahmadu Bello University, and is approved for contribution to knowledge and literacy presentation.

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DEDICATION

This thesis is dedicated to the Almighty Allah for His unquantifiable favours, my entire families, friends and well-wishers.

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ABSTRACT

This study, investigated the creep behaviour of Black Afara (*Terminalia ivorensis*) timber in accordance with EN 408 (2004) and EN 13153 (2002). The data were analysed based on the Eurocode 5 (2004), Eurocode 0 (2002), JCSS (2006) and EN 384 (2004) specifications using Easyfit statistical package. The statistics of the reference material properties (density, bending strength and modulus of elasticity) were calculated. The mean value of the density was found to be 449.24kg/m^3. The corresponding coefficient of variation is 15%.The mean values of the modulus of elasticity is 16171N/mm^2, and the corresponding coefficient of variation is 21%. For the bending strength, the mean value was given by 81.05N/mm^2. The corresponding coefficients of variation is 16%. The mean values were adjusted to 12% and 18% moisture content, to agree with the European and Nigerian reference moisture contents. Five theoretical distribution models (normal, lognormal and gumbel, weibull and frechet) were fitted to the reference material properties using kolmogorov smirnov statistical distribution fitting technique. The best fit theoretical distribution models were found to be normal distribution for density, Lognormal distribution for modulus of elasticity and Weibull for bending strength. The Terminalia ivorensis timber specie was graded in accordance with the requirements of EN 338 (2009). This yielded the appropriate strength of D18. One-year creep test was measured from the laboratory experiments on *Terminalia* ivorensis timber samples. The creep data were fitted to linear, exponential and logarithmic regression models. The coefficients of determination for each of the model was determined. The logarithmic model has the highest correlation with coefficient of determination of 0.941. This implied that, logarithmic regression model is the most appropriate to model the creep behaviour of the timber. The selection of the logarithm models was buttressed by the values obtain from regression modelling error analysis. Microstructure analysis was conducted on the *Terminalia ivorensis* timber specie using scanning electron microscope on the specimen. The analysis was conducted before and after creep deformation. The microstructure analysis revealed that, the cellular structure contained empty vessels which was found to have closed after creep deformation. This implied that, the application of the long term loading lead to the closure of the empty vessels within the cells microstructure, leading to the densification of the timber.

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NOTATIONS

β_v The coefficient of volumetric movement

ρb	Bulk density
ρd	Dry density
ρk	Characteristic density
ΔF	Load increment
Δw	Deflection increment
ρ_{12}	12% moisture adjusted density
ASTM	American Standard for Testing Materials
a	Distance between one load and the nearest support in four-point test setup
BS	British Standard
b	Width of section
EDX	Energy-dispersive X-ray
E_m	Bending modulus of elasticity.
E_m	Reference bending modulus of elasticity
$E_{t,0}$	Tension Modulus of Elasticity parallel to grain
$E_{t,90}$	Tension Modulus of Elasticity perpendicular to grain
$E_{c,0}$	Compression Modulus of Elasticity parallel to grain
$E_{c,90}$	Compression Modulus of Elasticity perpendicular to grain
E_{mean}	Mean modulus of elasticity
$E_{0,05}$	Five percentile modulus of elasticity

$E_{m,12}$	12% moisture content adjusted modulus of elasticity
$E_{measured}$	Measured modulus of elasticity
f_m	Bending strength
F_{max}	Maximum applied load
$f_{m,k}$	Characteristic bending strength
$f_{t,0,k}$	Characteristic tension strength parallel to grain
$f_{t,90,k}$	Characteristic tension strength perpendicular to grain
$f_{c,0,k}$	Characteristic compression strength parallel to grain
$f_{c,90,k}$	Characteristic compression strength perpendicular to grain
$f_{v,k}$	Characteristic shear strength
$f_{m,12}$	12% moisture content adjusted bending strength
$f_{measured}$	Measured density
GOF	Test of Goodness of Fit
G_v	Shear Modulus
I	Moment of inertia
JCSS	Joint Committee on Structural Safety
K_{mod}	Load duration factor to timber
K_{def}	Factor related to calculation of creep deformation
k_h	Section depth adjustment factor
L	Span of test timber beam
MOE	Modulus of Elasticity
MC	Moisture Content
mb	Bulk mass
m_0	Oven dry mass
NCP	Nigerian Code of Practice

NDPs	Nationally Determined Parameters
R_m	Reference bending strength
$R_{t,0}$	Tension Strength parallel to grain
$R_{t,90}$	Tension Strength perpendicular to grain
$R_{c,0}$	Compression strength parallel to grain
$R_{c,90}$	Compression strength perpendicular to grain
R_v	Shear Strength
$R_{h,0}$	Embedding Strength parallel to grain
$R_{h,90}$	Embedding Strength perpendicular to grain
SEM	Scanning Electron Microscopy
u	Moisture content at test
V	Volume of sample
W_{creep}	Creep deflection,
W_c	Camber deflection,
W_{inst}	Instantaneous deflection,
$W_{net,fin}$	Net final deflection
W	Section modulus

CHAPTER ONE

INTRODUCTION

1.1 Background

Wood is one of the oldest and most used materials known. From a simple log lying over a creek acting as a footbridge to large multi-storey timber buildings. It is usable for a wide range of structures (Trygve, 2015).

The term timber is frequently used to referto wood that is suitable for building or structural usage. It is one of the most frequently used building materials in both ancient and modern engineering constructions. Recently, the use of timber structures has increased in the construction industry due to attributed advantages such as environmentally friendly nature of timber, fully renewable potential and low handling costs (Afolayan, 2005; Hassani *et al.*, 2014). Timber is widely available natural resources throughout the world, which with properly managed wood plantation, there is potential for continuous and sustainable supply of raw timber materials.

In addition, it exhibits unique material properties; it is a light weight material and, compared to its weight, the strength is high; the strength/weight ratio is even higher than for steel that is why it is used widely as a structural material for roofing system and pedestrian or bicycle bridges. Also it has low modulus of elasticity compared to concrete and steel (Shuaibu, 2010), this implies low stiffness capacity and consequent poor resistance to deflection in service.

The above mentioned attributes among others, gave rise to the acceptance of timber worldwide as building material that can compete stiffly with the conventional/popular

concrete and steel in the arena of the building industry with considerable advantages of low embodied energy, low carbon impact, and sustainability.

Unfortunately, itsstrong hygroscopic character basically affects all related mechanical properties leading to degradation of material stiffness and strength over the service life resulting in the loss of capacity and consequently structural integrity even after being in use for decades (Hassani *et al.,* 2014).

In addition to the hygroscopic character, time-dependent phenomena like long-term visco-elastic creep (Liu, 1993) and mechano-sorption under changing environmental conditions (Houska and Bucar, 1995; Hanhijarvi, 1995) also affect strength and stiffness of timber in service.

The time-dependent behaviours of wood has been widely investigated, and the following measures of time-dependent response are commonly used in experimental investigation: creep, the increase of the deformation with time, under a sustained applied action; relaxation, the stress decay under constant deformation; stiffness variation in dynamic mechanical analysis (Ferry, 1980); and rate of loading (or straining) effects (Boyd and Jayne, 1982).

These basic techniques can also be generalized to include recovery (the recovery of strain once a creep load is removed) and more general loading histories (Barrett, 1982). In order to investigate the time-dependent behaviours of Terminalia ivorensis in this study, the creep technique was employed.

The prognosis of the long-term behaviours of timber structures under service loads and environmental influence is one of the most discussed issues in research and design of timber structures(Foschi and Barrett, 1982). Since deformations developed are due to

very complicated physical and mechanical time-dependent properties, a wide range of factors, such as variable moisture and temperature conditions, stress level, span-depth ratio, the structure of wood and other factors affect the wood and should be taken into consideration to enable the prediction of deformation in timber structures more accurately for design purpose.

There have been serious investigations devoted to load duration effects in wood carried out by researchers in different countries up to now, and more extensive reviews on the topic have been documented by Morlier (1994), Hunt (1999) and Dinwoodie, (2000). Nevertheless, an establishment of a plan mathematical model and/or definition of numerical parameters for prediction of final deformation for Nigerian timber species are not available.

The serviceability limit state of timber structures is seriously influenced by the increase of deformation due to creep of material. The creep process lead to a time-dependent increase of deformation of structural elements that can cause inadmissible deformation and even collapse of an entire construction. Lots of rheological models have been designed by various researchers (Bodig, 1993; Toratti, 1992; Hanhijarvi, 2000; Martensson, 1992; Dubois *et al.,* 2005; Chassagne *et al.,* 2006; Dinwoodie *et al.,* 1990; Pierce *et al.,* 1985) during the last decades with the aim of describing and simulating the time dependent behaviour of a natural viscoelastic material-wood. However, the mathematical models derived contain a great variety of constants to be determined by large sample tests.

Wood loaded under a long period of time will experience an instant deformation right after load is applied. With time, creep deformations will develop in the loaded specimen.

Part of the deformation will be elastic and disappear right after the load is removed. The other part is a plastic deformation that is due to viscous flow within the molecules that leaves a permanent deformation (Hoffmeyer, 1990).

Timber which is a product from wood differs from other capillary-porous material, for it is living and is composed of cells. These cells can swell and shrink to a relatively great extent as they absorb or release moisture (Krus and Vik, 1999), resulting in variability within and between timber species. The inherent variability of timber which is unique in its structural and mode of growth results in characteristics properties which are distinct and more complex than other common structural materials such as steel, concrete and brickwork (Shuaibu, 2010). Its hygroscopic character however, affects all related mechanical properties leading to degradation of material stiffness and strength over the service life resulting in the loss of capacity and consequently structural integrity even after being in use for decades (Hassani *et al.*, 2014).

The focus of this research is on Nigerian grown *Terminalia ivorensis* (black Afara) timber species which is commonly used within the construction industry in Nigeria. The rheological properties studied established relationships between stress, strain, rate of strain, and time.

1.2 Problem Statement

The serviceability limit state of timber structures is greatly influenced by the increase of deformation due to creep of material. The creep process leads to a time-dependent increase of deformation of structural elements that can cause inadmissible deformations and even collapse of an entire structure. A lot of different rheological models have been designed by various researchers (Bodig, 2000; Toratti, 1992;

Hanhijarvi, 2000; Mårtensson, 1992; Dubois et al. 2005; Chassagne et al. 2006; Dinwoodie et al. 1990; Pierce et al. 1985) during the last decades with the aim of describing and simulating the timedependent behaviours of a natural viscoelastic material-wood. However, the mathematical models derived contain a great variety of constants to be determined by large sample tests.

Traditionally, structural design in Nigeria is based on British Standard. Eurocode 5, which is the current design code for timber structures in Britain. This code is based on limit state design approach that requires the treatment of the ultimate and serviceability limit states separately. A deterministic constant, k_{dep} is used in Eurocode 5 to accommodate creep of timber. There is the need to develop a model based on creep test data that is capable of adequately but simply predicting timber creep, in order to fully accommodate timber rheology in design.

1.3 Justification of Research

As reliability based design replaces traditional deterministic design practices, a long-term creep law for wood becomes necessary to account for the time-dependent behavior of wood.

Improvements must be sought in our knowledge of the long-term behavior of non-lumber materials. This information could help improve structural modeling, and also clarify questions of the linkages between strength degradation and creep, as well as the interaction between environmental effects, threshold levels for strength, upper limits of creep deformations, etc.

Furthermore, Leichti *et al.,* (1990) cited the lack of information about the long-term behavior of structural wood composites as the main reason why designers are reluctant to use them in primary structural applications, such as beams and columns.

Nigeria has very vast timber resources. However, the resources are not fully utilized to their maximum capacity in the area of design and construction. The area it gained wide applicability is in roof truss systems which is based on prescriptive design. To effectively design timber structures based on the current designed philosophy of the Eurocode 5, material properties, strength classification as well as time dependent behaviour of timber must be established.

1.4 Aim and Objectives

1.4.1 Aim of Study

The aim of this study is to investigate the creep behaviour of black afara (*Terminalia ivorensis)* timber.

1.4.2 Objectives of Study

The objectives of the study to achieve the aim are as follows;

1. To determine the reference material properties; density, modulus of elasticity and bending strength of *Terminalia ivorensis* (black afara) timber specie according to EN 338 and Eurocode 5 as well as the other material properties; tension strengths parallel and perpendicular to grain, compression strength parallel and perpendicular to grain, shear strength and shear modulus.

2. To fit the requisite properties of the Terminalia Ivorensis (Black Afara) timber to adequate stochastic distribution models using Kolmogorov-Smirinov test in easyfit statistical software package.
3. To determine deformation from one-year creep test on *Terminalia ivorensis* timber specie and performregression analysis to develop time-dependent creep prediction models for the timber under investigation.
4. To investigate the microstructure of Nigerian grown *Terminalia ivorensis* timber before and after creep in order to find out the effect of creep at the micro level.

1.5 Scope of the Research

This study is focused on Nigerian grownBlack Afara(*Terminalia ivorensis*) timber specie. The strength and stiffness properties test carried out are those reference properties specified by EN 384 (2004) and Eurocode 5. Creep behaviour of *Terminalia ivorensis* timber species was measured and modelled over a period of three hundred and sixty days (one-year) according to DIN 50, 119 (1978). The developed statistical model considered only two variables; creep deformation and time. Effect of moisture content and temperature were implicitly accommodated.

1.6 Limitation of the Research

The following are the limitation of the research:

i. The timber samples were not obtained directly from the parent trees, but from open market already converted. The actual age of the timber could not be established.

ii. The results obtained from this thesis is based on standard controlled laboratory condition. There may be variation from what is obtained in the field.

iii. Three creep testing machines were used for the long term creep tests and each machine can accommodate only one sample. Therefore, only three samples were used for the creep tests.

iv. The mathematical models developed are only for one-year creep tests. Creep prediction with the developed models may only be approximate if used for more than one-year creep.

CHAPTER TWO

LITERATURE REVIEW

2.1 Preamble

Timber is an efficient building material, not only in regard to its mechanical properties but also because it is a highly sustainable material. It is considered a sustainable building material because it is derived from a renewable source and has a low embodied energy (Chanakya, 2009; Porteous and Kermani, 2007; Robert, 2009).

Embodied energy reflect the minimal non-renewable energy used in the production of timber and its application in construction. It has sound thermal properties, meaning that timber structures rely less on carbon-emitting heating and cooling appliances than building construction of other material. Wood is also durable, since many products, particularly hardwoods have a service life of greater than 50 years, and often require little energy in maintenance (Robert, 2009). Wood can also be recycled, which is important in terms of storing carbon through the life of a product and its transformation. Wood is inexpensive material. Forest is a wood factory which produces wood using only solar energy (Dorina *et al*, 2012).

Timber is a widely available natural resource in many countries; with proper management, there is a potential for a continuous and sustainable supply of raw timber material in the future. Due to the low energy use and the low level of pollution associated with the manufacturing of timber structures, the environmental impact of timber structures is much smaller than for structures built using other building materials (Porteous and Kermani, 2007).

The concept of environmental performance becomes clearer when wood is compared with steel and concrete. Recent research studies confirmed that houses made from wood present significantly lower risk for the environment. Wood-based building materials require less energy to be produced, emit less pollution to the air and water, contribute with lower amount of CO_2 to the atmosphere, are easily disposed of or recycled, and are derived from a renewable resource.

From the foregoing, it can be easily concluded that the environmental advantages of wood compared to steel and concrete are obvious.

Life-cycle analysis results for the steel-framed versus wood-framed home (Dorina *et al*, 2012) showed that the steel-framed home use 17% more energy; had 26% more global warming potential; had 14% more air emissions; had over 300% more water emission and had about the same level of solid waste production than timber. Analysis results for the concrete-framed home used 165 more energies; had31% more global warming potential; had 23% more air emission; had roughly the same level of water emission and produced 51% more solid waste.

Timber is an advantageous building material.Its strength is high; the strength to weight ratio is even higher than for steel (Porteous and Kermani, 2007: Shuaibu, 2010). However, timber is still not utilized to its full potential in the building and construction sector considering its beneficial properties. Attributes such as high performance in regard to reliability, serviceability and durability are generally not associated with timber as a building material. One of the main reasons for this is that timber is a highly complex material; it actually requires a significant amount of expertise to fully appreciate the potential of timber as a structural building material.

In addition to this, there are still a number of issues which need to be further researched before timber materials can achieve the same recognition as a high quality building material such as example, steel and concrete.

Timber is an abundant, renewable and recyclable material, which has been used by human for thousands of years. Its use in construction is still widespread, ranging from structural frames to floors, paneling, doors, interior and exterior woodwork, and furniture, among its multiple uses in an average dwelling (FPL, 1999).

Three polymeric materials make up the wood cells: cellulose, hemi-cellulose and lignin (Kollmann and Cote, 1968). Cellulose makes up the cell walls, and provides the tensile strength of the wood matrix. Hemicellulose is similar to cellulose, and grows around the cellulose fibres. Lignin gives rigidity to the wood, allowing trees to grow upright; it cements the cells together, thus accounting for the compressive and shear strengths of wood (Kollmann and Cote, 1968; Moraes, 2003).

These three polymers form an inhomogeneous and anisotropic material, which exhibits great variability among different species.

In general, tree species can be divided into two major groups, hardwoods and softwoods. Hardwoods are porous, and present greater hardness than softwoods (although some exceptions exist) (FPL, 1999).

Timber structures have traditionally been built using heavy timber frames, with the walls being constructed of various materials such as interwoven branches and split logs in the very early versions of these types of structures (as early as 6500 BC), and later using plastered panels and bricks (Foliente, 2000). Other forms of timber structures are palisade-type buildings and log-cabin constructions. Roof structures, as integral part of

the building, have also traditionally been made in wood, and are still popular to this day especially in Nigeria.

Timber roof structures have two basic forms: simple horizontal beams, or more complicated rafters being supported by the frame. Combinations of these two types have developed into hammer-beam roofs, which were used with great skill during the Renaissance, and into trusses, where originally the struts were also under flexion, unlike modern trusses where all the joints are assumed to be pinned (Foliente, 2000).

The coming of the industrial revolution marked the appearance of industrially built planks, boards and nails which spawned the appearance of new construction techniques, especially in the USA, where new framing methods reduced labour costs, increased the flexibility in construction and allowed for prefabrication (Foliente, 2000). These light frame construction methods are nowadays the predominant form of construction in residential and low-rise buildings.

Other technological advances developed in this period are the glued laminated timber, first used in Bavaria in 1809 (Pedro, 2008) and improvements in wood trusses (Foliente, 2000). Glued laminated timber in its present form was developed in the twentieth century, as well as another important innovation, plywood (Foliente, 2000).

2.2 Structure of Wood

Wood is composed of cellulose, lignin, hemicelluloses, and minor amounts (usually less than 10%) of extraneous materials contained in a cellular structure. Variations in the characteristics and proportions of these components and differences in cellular structure make woods heavy or light, stiff or flexible, and hard or soft. The

properties of a single species are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate (Falk, 2010).

Structural timber is sawn (milled) from the trunk of the tree, which provides rigidity, mechanical strength and height to maintain the crown. Trunk resists loads due to gravity and wind acting on the tree and also provides for the transport of water and minerals from the tree roots to the crown. Roots, by spreading through the soil and acting as a foundation, absorb moisture-containing minerals from the soil and transfer them via the trunk to the crown. Crown, comprising branches and twigs to support leaves, provides a catchment area producing chemical reactions that form sugar and cellulose that cause the growth of the tree (Porteous and Kermani, 2007).

The part of the tree that is of importance for the use of wood in the construction industry is its trunk. Figure 2.1 below shows a typical of the cross section of a tree trunk.

Features such as bark, the outer part of which is a rather dry and corky layer and the inner living part. The cambium, a very thin layer of cells underside the inner bark, is the growth centre of the tree. New wood cells are formed on the inside of the cambium (over the old wood) and new bark cells are formed on the outside and as such increasing the diameter of the trunk. Although tree trunks can grow to a large size, in excess of 2 m in diameter, commercially available timbers are more often around 0.5 m in diameter (Porteous and Kermani, 2007).

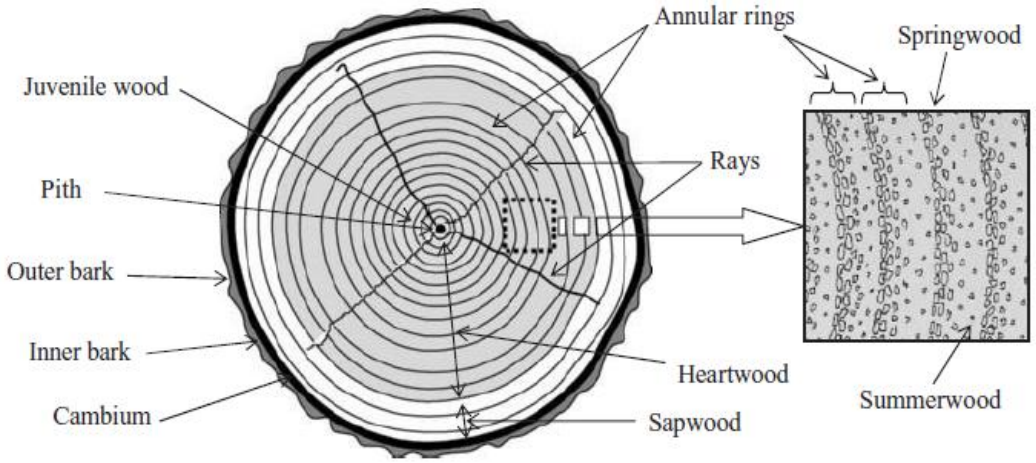

Figure 2.1: Cross section of a tree trunk (Porteous and Kermani, 2007).

In countries with a temperate climate, a tree produces a new layer of wood just under the cambium in the early part of every growing season. This growth ceases at the end of the growing season or during winter months. This process results in clearly visible concentric rings known as annular rings, or growth rings. In tropical countries, where trees grow throughout the year, a tree produces wood cells that are essentially uniform. The age of a tree may be determined by counting its growth rings (Porteous and Kermani, 2007).

The annular band of the cross-section nearest to the bark is called sapwood. The central core of the wood, which is inside the sapwood, is heartwood. The sapwood is lighter in colour compared to heartwood and is 25–170 mm wide depending on the species (Porteous and Kermani, 2007). It contains both living and dead cells and acts as a medium for transportation of sap from the roots to the leaves, whereas the heartwood, which consists of inactive cells, functions mainly to give mechanical support or stiffness

to the trunk. As sapwood changes to heartwood, the size, shape and the number of cells remain unchanged.

In general, in hardwoods the difference in moisture content of sapwood and heartwood depends on the species but in softwoods the moisture content of sapwood is usually greater than that of heartwood. The strength and weights of the two are nearly equal.

Sapwood has a lower natural resistance to attacks by fungi and insects and accepts preservatives more easily than heartwood (Porteous and Kermani, 2007).

2.3 Types of Timber

Trees and commercial timbers are divided into two types: softwoods and hardwoods. This terminology refers to the botanical origin of timber and has no direct bearing on the actual softness or hardness of the wood as it is possible to have some physically softer hardwoods like balsa from South America and wawa from Africa, and some physically hard softwoods like the pitch pines (Porteous and Kermani, 2007).

2.3.1 Softwoods

Softwoods are those woods that come from gymnosperms (mostly conifers), which are generally needle-leaved evergreen trees such as pine (Pinus) and spruce (Picea) (Wiemann, 2010).

Porteous and Kermani, (2007) reported that the leaves comprise of single cells called tracheids, which are like straws in plan, and they fulfill the functions of transporting water and mineral salts. Rays, present in softwoods, run in a radial direction

perpendicular to the growth rings. Their function is to store food and allow the convection of liquids to where they are needed. Figure 2.2 below shows a typical structure of soft wood.

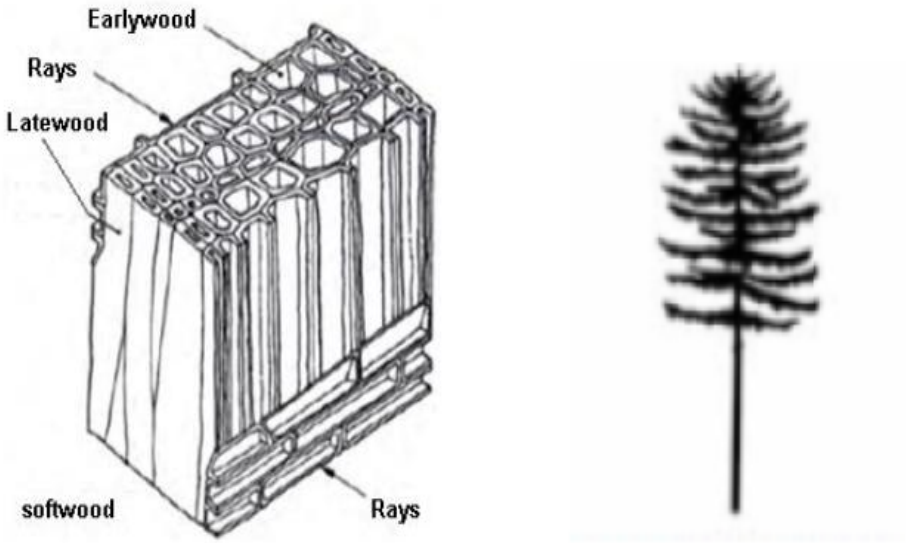

Figure 2.2: Typical structure of softwood, magnified 250 times (Bartůňková, 2012).

2.3.2 Hardwoods

Hardwood are from deciduous trees, most of whichshed their leaves at the end of each growing season (Wiedenhoef, 2010). The cell structure of hardwoods is more complex than that of softwoods. They have thick-walled cells, called fibres, providing the structural support and thin-walled cells, called *vessels*, providing the medium for food conduction.

The Hardwood characteristics according to Porteous and Kermani, (2007) are as follows;

i. Hardwoods grow at a slower rate than softwoods, which generally results in a timber of high density and strength, which takes time to mature, over 100 years in some instances.

ii. There is less dependence on preservatives for durability qualities.

iii. Due to the time taken to mature and the transportation costs of hardwoods, as most are tropical, they tend to be expensive in comparison with softwoods.

Figure 2.3 below shows a typical structure of hardwood.

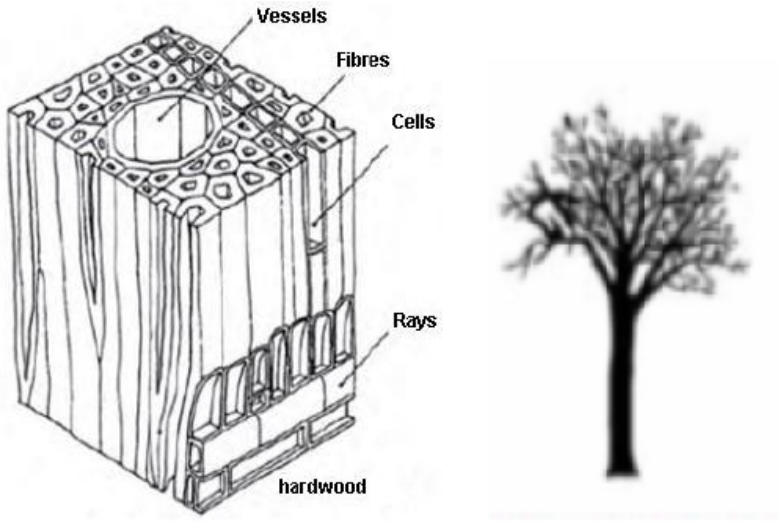

Figure 2.3: Typical structure of hardwood, magnified 250 times (Bartůňková, 2012).

2.4 Timber as a Structural Material

Timber is defined as wood that is only used for engineering purposes. The vast use of timber in construction industry in Nigeria, especially for roof trusses, could be linked to its abundance all over the country. It is not only found in almost everywhere but also very cheap. It is one of the cheapest construction materials in the country (Bartunkova, 2012).

In the past, stakeholders have constrained technical knowledge of the use of timber. This is as a result of the fact that technical building and engineering training/education has favored steel, concrete and masonry over the timber, as wood are often seen as an aesthetic material rather than engineering (Wiedenhoef, 2010).

Recently, the interest in designing timber structures has steadily increased. The reason for this being an increased focus in society on sustainability and environmental aspects but also due to the positive effects of timber materials on the inner climate in residential buildings and excellent architectural possibilities (Wiedenhoef, 2010). Furthermore, timber has been found technically and economically competitive compared with steel and concrete as a building material for a broad range of building structures such as e.g. large span roof structures and residential buildings.

Only then can a consistent basis for the design of timber structures be insured for the benefit of the society in general and for the parties with interest in the application of the timber as a building material in particular (Wiedenhoef, 2010).

In order to gain a better understanding of the reason for the special behavior of wood and timber material it is helpful to start thinking about where the wood and the timber are 'produced'; in the stem of a tree (Kohler, 2007).

In spite of the aforementioned advantages, unfortunately the strong hygric dependence of basically all mechanical properties render many innovative ideas futile. In addition, time-dependent phenomena like long-term visco-elastic creep (Holzer et al., 1989; Liu, 1993) and mechano-sorption under changing environmental conditions (Houska and Bucar, 1995; Bengtsson, 1999; Hanhijarvi, 2000) can accelerate degradation of stiffness and strength over the life-time of a structural wood component and result in the loss of capacity and consequently structural integrity even after being in use for decades.

2.5 Properties of Timber

Wood is a complex biological structure composed of many chemistries and cell types that all together ensure conduction of water from the roots to leaves, mechanical support of the plant body and storage of biochemicals. Wood properties can be of physical, mechanical, chemical, biological or technological essence (Kollmann and Sachs, 1967; Bartunkova, 2012).

2.5.1 Physical Strength Properties

Wood is a hygroscopic material, which means that it takes on moisture from the surrounding environment. Moisture exchange between wood and air depends on the relative humidity, temperature of the air and the current amount of water in the wood (Glass and Zelinka, 2010; Bartunkova, 2012).

2.5.1.1 Moisture content (MC)

Many physical and mechanical properties of wood depend upon the MC of wood. Green wood is usually defined as freshly sawn wood where the cell walls are completely saturated with water and additional water resides in the lumina. The moisture content of green wood can range from about 30% to more than 200%.

In green softwoods, the moisture content of sapwood is usually greater than that of heartwood. In green hardwoods, the difference in moisture content between heartwood and sapwood depends on the species (Glass and Zelinka, 2010).

2.5.1.2 Fiber Saturation Point

Moisture can exist in wood as free or bound water. Free water is the form of liquid or vapor in cell lumina and cavities while bound water is held by intermolecular

attraction within cell walls. The state when the cell walls are completely saturated (bound water) but no water exists in cell lumina is known as fiber saturation point (MC_{fs}). The fiber saturation point averages about 30% moisture content depending on individual species and individual pieces of wood (Bartunkova, 2012).

2.5.1.3 Equilibrium Moisture Content

Equilibrium moisture content is MC at which the wood is neither gaining nor losing moisture. EMC depends on both relative humidity and temperature.

2.5.1.4 Dimensional instability

Wood is dimensionally unstable when moisture content is lower than the fiber saturation point (MC_{fs}). This is because volume of the cell wall depends on the amount of bound water. Below MC_{fs} wood swells as it gains moisture or shrinks as it loses moisture. Shrinking and swelling usually result in warping, checking and splitting of the wood. (Glass and Zelinka, 2010).

Other physical properties usually discussed in books as buttressed by the codes of practice like NCP 2 (1973), are: Density, durability or resistance against insect and fungi attacks, resistance to impregnation by preservatives and movement (Swelling and shrinkage or dimensional changes) due to change in moisture content. These and more would be discussed in this section.

2.6 Some Common Nigerian Timber Species

Traditionally, timbers have been used to a significant extent in construction purposes and particularly building constructions (Aguwa and Sadiku, 2011). Over 80% of

the timber and timber products in Nigeria are utilized for different purposes. The major purpose of timber in building construction are roofing members, doors, frames, and staircases. They are also used for scaffolding and shuttering during construction. Others include: construction of fishing boats, poles and piles and rail sleepers etc. In road construction, large quantities of woods are also used for frameworks, pilling materials, road signboards, temporary shades, road paving plants in temporary construction site. They are also used at petroleum exploitation sites and in furniture industries.

There are different kinds of wood available in Nigeria, irrespective of their location and usage. They include: Apa, Black Afara, White Afara, Afromosia, Gmelina, Idigbo, Canarium, Okan, Antiaria, Lagos Mahogany, Berlinia, Ekki, Scented Guarea, Dry zone Mahogany, Camwood, Pterygote, Albizia, Alstonia, Makore, White sterculia, Owewe,Dist, Okwen, Obeche, Opepe, African Walnut, Mansonia, Teak, Ebony, Guarea, Iroko, Abura, Ogea, Pterocarpus, Erimado, Agba, Akpu, Danta, Celtis, walnut, etc NCP 2 (1973).

2.7 The Material Properties of Timber

A base set of material properties as well as some influencing factors are needed for a probabilistic design (Toratti and Ratta Maunus, 2002). Density, modulus of elasticity and bending strength are the reference material properties required to be determined explicitly from laboratory (Yang *et al*, 2008; Ziwa *et al*, 2006).

The properties and distribution of other material properties are linked with EN 384 (2004) and JCSS (2006) recommendations. As for the influencing factors, such as

moisture content effect, load duration effect, size and system effect, use is made of the deterministic value of such properties.

In BS 5268 Part 2 (2002)it is the strength that governed the design, but in the EC5 modulus of elasticity (MOE) and density are also important for both ultimate and serviceability limit states. The knowledge of MOE is of great importance for designing timber structures. It is normally the most important parameter for strength grading of sawn timber (Glos, 1995). The end-use of wood material, especially for structural timber is strongly related to MOE (Piter et al., 2003; Yang *et al*, 2008; Cave and Walker, 1994; Cown *et al*., 2003; Kennedy, 1995; Kliger *et al.*, 1995; Kumar, 2004).

Modulus of elasticity defines the relationship between stress and strain within the elastic region. Timber is considered to be an anisotropic material with three mutually perpendicular axes in the longitudinal, radial and tangential directions (Piter et al., 2003). The longitudinal modulus of elasticity is a quantitative measure of the stiffness of the wood along the grain. It is the most commonly measured elastic property and the most important elastic constant. Elasticity implies that deformations produced by the low stress are completely recoverable after loads are removed, and this is the accepted criterion of stiffness.

The values of MOE are of great importance for estimating deformation in timber structures, and for calculating timber columns (Thelanderson, 1995). The modulus of elasticity and bending strength are determined in the laboratory by testing timber beams in bending. In the bending test of structural members, two forms of loading were employed, the choice depending upon the type specified in codes of practice for the particular material.

In the first, a simply supported beam is subjected to a four-point loading system. Two concentrated loads are symmetrically applied to the test piece (beam) producing zero shear force and constant bending moment in the central span of the beam. The condition of pure bending is therefore achieved in the central span (EN 408, 2004).

The second form of loading system consists of a single concentrated load at mid-span. The loads are usually applied by a testing machine. Deflection is measured by a dial gauge placed underneath the beam, and load-deflection diagrams were plotted. BS 373 (1957) and ASTM D 143 (2006) set out method for measurement of MOE of small clear timber specimen based on the three-point bending, modulus of elasticity and bending strength are determined in the laboratory by testing timber beams in bending.

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The European Standard EN 408 (2004) establishes a third point loading test for calculating the local MOE, free of shear (clause 9), in the central third, but the code

additionally allows for obtaining the global MOE, over the whole span (clause 10). The mean values of MOE, and the characteristic values of bending strength and density allow to assign a timber specie to a strength class of the International Strength class System EN 338 (2009), and the other characteristic strength and stiffness properties can be calculated from those basic ones (Glos, 1995; Baltrusaitis and Pranckevocene, 2003; Antti and Ranta-Maunus, 2005; JCSS, 2006; Ridley-Ellis *et al*, 2008).

Wood density is often considered to be another very important wood property because of its strong influence on the quality of a wide range of solid wood and fiber products and has as such, received much attention.Bunn (1981) states that "density is probably the most important intrinsic wood property for most wood products", while Bamber and Burley (1983) pointed out that, "of all the wood properties, density is the most significant in determining end use".

Similarly, Zobel and van Buijtenen (1989) state that "density largely determines the value and utility of wood and overshadows the importance of other wood properties". However, the importance of density as an indicator of wood quality alone is debatable because variability is due to many intrinsic factors, defects and variations inherent in basic wood structures.

2.8 Codes of Practice for Design of Timber Structures

The only code of practice in Nigeria is the NCP 2 (1973) based on permissible stress design approach and was developed with reference to CP 112 (1967). The permissible stress design approach is also referred to as modular ratio or elastic design. ''In permissible stress design, the stresses in the structure at working loads are not

allowed to exceed a certain proportion of the yield stress of the construction material (Chanakya, 2009).

The CP 112 was severally revised, withdrawn and replaced with the BS 5268 which is also based on permissible stress design approach. BS 5268 was withdrawn and replaced with the Eurocode 5, on 31st March, 2010. The Eurocode 5, is based on the limit state design philosophy. However, Nigeria have not updated the Nigerian Code of Practice for timber structural design (NCP 2) (Kaura, 2014). In BS 5268, it is the strength that governed the design, but in the EC5 modulus of elasticity (MOE) and density are also important for both ultimate and serviceability limit states. Density, modulus of elasticity (MOE) and bending strength are the reference material properties required to be determined explicitly from laboratory (Yang *et al.*, 2008; Ziwa *et al.*, 2006). The properties and distribution of other material properties are linked with EN 384 (2004) and JCSS (2006) recommendations. As for the influencing factors, such as moisture content effect, load duration effect, size and system effect, use are made of the deterministic value of such properties. This implies that uncertainties related to material properties are not accommodated.

In addition, the Eurocode 5 recommends the use of deformation modification coefficients k_{def} that depends on load duration of timber of which five load duration classes were specified; permanent (greater than ten years), long term (six months to ten years), medium term (one week to six months) short term (less than a week) and no duration specified for instantaneous. Each duration class was assigned a specified k_{def}, the implication is that a single coefficient is used for a large range of timing. But in reality, this is not true because for a given loading time the effect of duration of loading varies.

Thus, the use of the code recommendation has problem of been conservative in treating time dependent nature of creep deformation.

2.9 Background on the Tested Timber Specie

All the timber species listed in the NCP 2 (1973) are hardwoods. Generally, hardwoods are used in structures where both sound mechanical performance and good natural durability are required (Blass et al., 1995).

Hardwoods offer certain advantages, particularly when using those timbers which are in the medium to high density ranges. Such material may allow the designer to use timber throughout structures, rather than having to switch to other materials for longer spans or heavier buildings (Breyer *et al.,* 1999). Another well-established building application for hardwoods is in the form of solid timber portal frames.

The availability of larger dimensions, and higher grade, as well as the inherently greater strength and stiffness provided by many hardwoods make it possible to consider hardwoods for application where steel or concrete would otherwise be regarded as necessary. The additional density of many of the species which are considered suitable for structural purposes also provides additional fire resistance. This is acknowledged by the indication of slower charring rates in the structural timber design codes, BS 5268: part 4 (1978) and Eurocode 5: part 1-2 (2004). *Terminalia ivorensis* specie was considered in this study.

Terminalia Ivorensis is a large deciduous forest tree ranging in height from 15 to 46m. It is branchless for up to 30m (Martin, 1984). The tree is native to Cameroon, Cote D'voire, Ghana, Guinea Bissau, Liberia, Sierra Leone and Nigeria (Cirad, 2009). The specie has a yellowish-brown wood. It is listed in EN 350-2 (1994). It is a class 3 (moderately durable) material. It is susceptible to termite attack. It has good nailing and gluing capacity. Based on the work of Cirad (2009), at 12% moisture content, the density of Terminalia Ivorensis is 500kg/m^3, crushing strength of 44MPa, static bending strength of 71MPa and modulus of elasticity of 11350MPa.

2.10 Strength Classes of Timber

Solid timber for structural application has to be strength graded prior to its use (Kisito *et al*, 2011). In order to remain economic, the grading process usually focuses on the most important physical and mechanical properties; density, modulus of elasticity (MOE) and bending strength (JCSS, 2006).

Timber is assigned to its appropriate strength class based on respective limits given in EN 338 (Kisito *et al*, 2011; Steiger and Arnold, 2009; Herald *et al*, 2007; Baltrušaitis and Pranckevičienė, 2003). Additional mechanical properties such as tensile and compressive strength parallel and perpendicular to the grain are derived from the basic property values by standard empirical relationships (EN 384, 2004; JCSS, 2006).

2.10.1 The Timber Strength Classification System

Prior to April 2010, the structural design of timber members in the United Kingdom is related to Part 2 of BS 5268, and is based on permissible stress design philosophy. Elastic theory is used to analyse structures under various loading conditions to give the worst

design case. Then timber sections are chosen so that the permissible stresses are not exceeded at any point on the structure.

BS 5268 part 2 (2002), on which the design of structural timber is based, was originally published as CP 112 in 1952, revised later in 1967 and, extensively revised in 1971.

The 'basic stresses' introduced in CP 112 were determined from carrying out short-term loading tests on small timber specimens free from all defects. The data was used to estimate the minimum strength which was taken as the value below which not more than 1% of the test results fell. These strengths were multiplied by a reduction factor to give basic stresses. The reduction factor made an allowance for the reduction in strength due to duration of loading, size of specimen and other effects normally associated with a safety factor, such as accidental overloading, simplifying assumptions made during design and design inaccuracy, together with poor workmanship.

Basic stress was defined as the stress that could be permanently sustained by timber free from any strength-reducing characteristics. Since 1967 there have been continuing and significant changes affecting the structural use of timber.

Research studies in the UK and other countries had shown the need for a review of the stress values and modification factors given in the original code. With the introduction of BS 5268 in 1984, the concept of' basic stresses' was largely abandoned and the new approach for assessing the strength of timber moved somewhat in line with limit states' design philosophy.

In 1996, Part 2 of BS 5268 was revised with a clear aim to bring this code as close as possible to, and to run in parallel with Eurocode 5: Design of timber structures, Part

1.1 General rules and rules for buildings. The overall aim has been to incorporate material specifications and design approaches from Eurocode 5, while maintaining a permissible stress code with which designers, accustomed to BS 5268, will feel familiar and be able to use without difficulty.

The concept of grouping timber into strength classes was introduced into the UK with BS 5268: Part 2 in 1984. Strength classes offer a number of advantages both to the designer and the supplier of timber. The designer can undertake his design without the need to check on the availability and price of a large number of species and grades which he might use. Suppliers can supply any of the species/grade combinations that meet the strength class in a specification. The concept also allows new species to be introduced onto the market without affecting existing specifications for timber.

The latest strength classes used in BS 5268: Part 2: 1996 relate to the European strength classes which are defined in EN 338 Structural timber. Strength classes.

There are a total of 16 strength classes, C14 to C40 for softwoods and D30 to D70 for hardwoods as given in Table 7 of BS 5268: Part 2 (1996). The number in each strength class refers to its 'characteristic bending strength' value, for example, C40 timber has a characteristic bending strength of $40N/mm^2$. Characteristic values larger than the grade stress values used in BS 5268: Part 2, as they do not include effects of long-term loading and safety factors.

One of the benefits of using characteristic value of material properties rather than grade stress is that it will make it easier to sanction the use of new material properties and component for structural purposes, since such values can be utilized immediately, without first having to determine what reduction factors are needed to convert them to

permissible or working values. In Table 2.1 below, typical grade stresses and characteristic values for timber strength class D70 are presented.

Table 2.1: Strength Properties of D70 Timber Based on BS 5268 and EN 338

Material Property	Strength class D70	
	Grade Stress (BS 5268)	EN 338
Bending Strength Parallel to Grain	23.0	70.0
Tension Parallel to Grain	13.8	42.0
Compression Parallel to Grain	23.0	34.0
Shear Strength	2.60	6.0

Source: BS 5268 (2002); EN 338 (2009).

2.10.2 Timber Grading System in the Nigerian Code of Practice (NCP 2)

NCP 2 (1973) still remained the structural timber design code in Nigeria. This code is based on the permissible stress design philosophy, with reference to the CP 112 (1967). With the introduction of BS 5268, CP 112 had been withdrawn in 1984. To date NCP 2 was never subjected to any revision and remained the authoritative document to timber structural design in Nigeria.

The basic stresses in the NCP 2, is similar to that in CP 112. The timber species are classified into 7 strength groups N1 to N7, with N1 given the strongest species. Each specie is also classified according to the ability of the heartwood to resist attack by fungi and insects.

The code also has five durability classes namely, very durable, durable, moderately durable, non-durable and perishable. As the ease with which the timber can be impregnated when it is used under condition which favour decay or attack by insects is important, five classes indicating the resistance of the heartwood to impregnation were

given in the code. These are; permeable, moderately resistant, resistant, very resistant and extremely resistant. Table 2.2 give the NCP 2, strength grades of the timber specie tested in this study.

Table 2.2 Grades of the Tested Timber Specie According to NCP 2 (1973).

Timber Specie	Standard Name	Strength Group	Natural Durability	Resistant to Impregnation
Terminalia ivorensis	Idigbo	N4	Durable	Extremely Permeable

Source NCP 2 (1973)

2.11 Effect of Load Duration on Timber Structures

Wood experience a significant loss of strength and stiffness when loaded over a period of time. The effect of ten years load duration may amount to a strength loss of approximately 40 % for solid wood (Toratti, 2004; Kohler and Svensson, 2002; Larsen, 2001). This phenomenon is known as creep-rupture – often called the duration of load (DOL) effect. The issue has been a subject of particular interest for everyone in the timber engineering community concerned with safe and efficient engineering design. Research on both clear wood (Wood, 1951) and structural timber (Hoffmeyer, 1990 and Madsen 1992) sustaining long-term constant load is well documented in the literature.

2.11.1 The Eurocode 5 Strength Modification Factor for Load Duration K_{mod}

Load duration factors to account for timber design under sustained load are given in Eurocode. The k_{mod} is based on timber service and load duration classes. The service classes are defined in clause 2.3.1.3 of the Eurocode 5 as follows;

Service class 1 refers to timber used internally in a continuously heated building. The average moisture content likely to be attained in service condition is 12%.

Service class 2 refers to timber used in a covered building. The average moisture content likely to be attained in service condition if building is generally heated is 15%, and if unheated, 18%.

Service class 3 refers to timber used externally and fully exposed. The average moisture content likely to be attained in service condition is over 20%.

Table 2.3: Eurocode 5 Load Duration Classes

Load duration class	**Order of accumulated Duration of Characteristic Load**	**Example of loading**
Permanent	Greater than 10 years	Self-weight
Long-term	6 month to 10 years	Storage
Medium-term	1 week to 6 month	Imposed floor load
Short-term	Less than one week	Snow, maintenance
Instantaneous		Wind, impact

Source: Eurocode 5: Part 1.1 (2004)

The load duration classes are given in Table 1 of the National Annex to Eurocode 5, as presented in Table 2.3, and based on the service and load duration class, the K_{mod} are established, as shown in Table 2.4.

Table 2.4: K_{mod} for Solid Timber (Eurocode 5)

Load Duration Class	**Service Class**		
	Class 1	**Class 2**	**Class 3**
Permanent	0.60	0.60	0.50
Long term	0.70	0.70	0.55
Medium term	0.80	0.80	0.65
Short term	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90

Source: Eurocode 5: Part 1.1 (2004).

2.12 Creep

As is well known, the static testing of materials is often not sufficient for the determination of their behavior for present-day applications. The rate of application of the load and the time that the load remains in place are extremely important factors. Consideration of these factors requires that information be obtained about behavior with respect to time.

The time-dependent deformation phenomenon under sustained loading of wood is known as creep. Such time-dependent characteristics of materials are known as rheological properties (Nordstrom and Sandberg, 1994). The type of deformation called creep is a time dependent increase in deformation beyond the immediate elastic deflection that is surpassing the deflection which is immediately recoverable upon removal of the applied force.

If deformation (expressed as strain, elongation, or deflection) is plotted against time, a curve similar to that shown in Figure 2.4 will result. The curve can be divided into four parts. The initial deformation, OA, is that occurring when the load is applied. It is, for all practical purposes, usually considered to be instantaneous and, depending upon the magnitude of the load, may be composed of elastic, delayed elastic and plastic deformations.

The primary stage, AB, of the creep curve, also called the transient creep stage, describes a period during which the rate of deformation constantly decreases. This decrease continues until the secondary stage, BC, is attained. The secondary stage, or steady-state part of creep, is usually considered the period of constant rate of

deformation. Thus, BC is a straight line of minimum slope. This region is joined smoothly to a tertiary stage, CD, in which the deformation rate increases and failure of the specimen ultimately occurs.

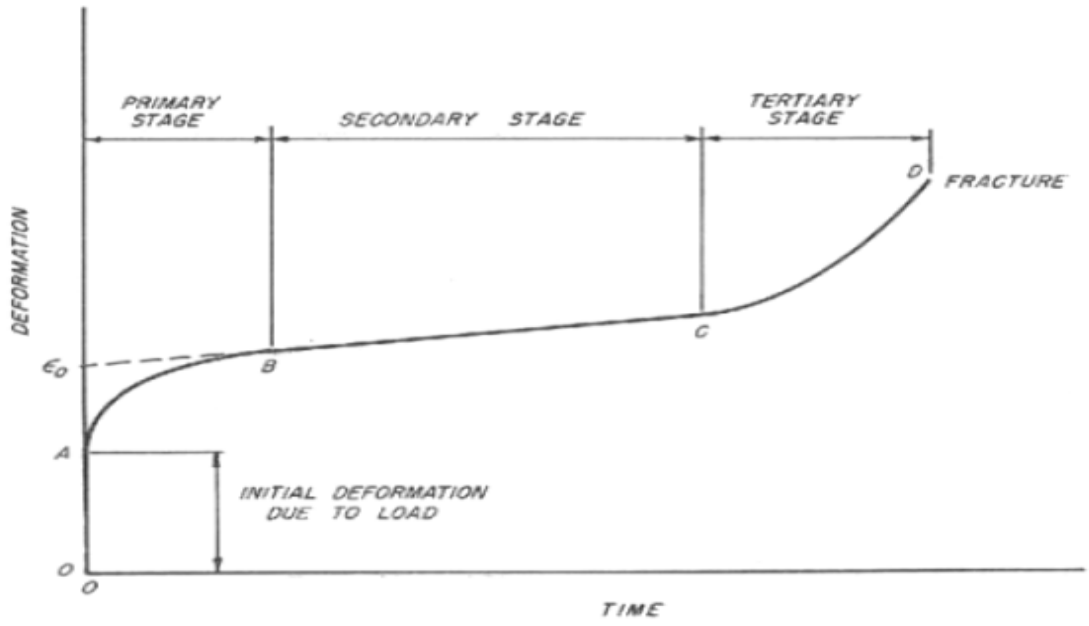

Figure 2.4: Idealised Constant-Load Creep Curve

2.12.1 Creep of Wood

Wood is a complex, anisotropic, porous, naturally expanded material. The composition varies slightly from species to species, but the most important constituents common to all are cellulose, hemicellulose, and lignin. Cellulose and hemicellulose make up 70 to 80 percent of the weight of ovendry wood, and lignin 20 to 30 percent.Analogous to concrete, wood is a special structural material that interacts with the environment to undergo complex changes in its properties.

The cellulose molecule has hydroxyl (-OH) groups at regular intervals. These are responsible for the adsorption of water molecules and for bonding cellulose molecules to

each other in the crystallites that form the minute structure of the cell wall. Although the resulting individual bonds are weak, there are so many that the total binding energy is great enough to prevent the separation of the cellulose chains by water. This force also prevents the melting of cellulose at high temperatures.

This exclusion of water from the interior of the crystallite leads to the adsorption of water only in the amorphous regions and on the surfaces of the crystallites. In a humid atmosphere dry wood adsorbs moisture, the water molecules becoming attached to the accessible hydroxyl groups. The attachment produces swelling of the wood, principally in the radial and tangential directions and to only a slight extent longitudinally, since the fibrils are approximately parallel to the axis of the cell. That unequal shrinkage stresses may contribute to creep. (William, 1959).

The presence of water facilitates plastic strain in wood by weakening bonds between some of the cellulose chains. An increase in temperature will weaken the bonds by increasing thermal molecular movement.

If applied strains are not large enough to break bonds, the wood will behave elastically. If the strains do break bonds, there will be differential movement between the chains with exchange of bonds and inelastic strain. Permanent strain can also occur upon rupture of molecules or by shearing of the crystallites. These processes would be more likely to occur in the final stages of creep or at a very high creep rate.

In the light of the structure and chemistry of wood, these assumptions about creep mechanisms are valid. It must be remembered, however, that wood is a natural product and, as such, has a host of growth features such as knots, pitch pockets, and grain

irregularities, that introduce an empirical factor into the description of the creep process. (William, 1959).

Accordingly, it is useful to organize the review relative to constant and variable environmental conditions. It was pointed out by Bodig (1993) that creep is often much more sensitive to temperature, moisture content, and physical aging than elastic properties. Creep, the time-dependent deformation under constant load; relaxation, the stress decay under constant deformation; stiffness variation in dynamic mechanical analysis (Ferry, 1980); and rate of loading (or straining) effects (Boyd, 1982).

The correct prediction of the deformations of timber structures is an important question in the design process. The mechanical performance of timber structures is usually regulated by the deflection of the member rather than by the actual strength. One reason being that the ratio of the strength of wood to its elastic modulus is very high as compared to other building materials (Toratti, 1992). But perhaps a more important reason is that the increase of deformation with loading time is known to be very significant for wood. From previous experience, the creep of wood in constant humidity conditions is of a moderate magnitude: for low stresses, the elastic deformation can be multiplied roughly by a factor of 1.4 to account for a one-year load duration. But if the humidity conditions are variable, the creep magnitude is known to be several times higher. This has been termed the mechano-sorptive effect.This effect has been known for a long time, but its quantitative prediction and impact on timber structures subjected to natural humidity and loading conditions is poorly understood (Boyd, 1982).

Timber structures are subjected to a variable climate by nature. An outdoor sheltered environment could be considered as the most severe condition to which load carrying

timber is used. An indoor climate is also variable, but usually with a lower cycle amplitude (Yahiaoui, 1991).

2.12.1.1 Effect of Environment on Wood

A model was derived by Toratti (1992) to predict the creep of wood in varying environment humidity when subjected to bending, tension or compression parallel to grain. This method is a combined transient moisture transfer analysis and a deformation analysis. The method is used to analyse test results in the study of constitutive equations as well (Toratti, 1992).

Many rheological studies of wood were concerned with identifying conditions under which wood may be modeled as a linear viscoelastic material. This is reflected in a review of creep experiments by Schniewind (1968). The experiments indicate that within certain limits of stress and at constant moisture content and temperature wood can be treated as a linear viscoelastic material. This finding has been confirmed by other studies (Bach 1965; Bazant 1985; Grossman *et al.*, 1969; Nakai and Grossman 1983; Pentoney and Davidson 1962; Schaffer, 1972). For example, Schaffer (1972) draws the following conclusion from evidence in the literature: "Wood behaves nonlinearly over the whole stress-level range, with linear behavior being a good approximation at low stresses. Because of this nearly linear response at low levels of stress, Boltzmann's superposition principle applies to stress-strain behavior for stresses up to 40% of short time strength.

2.12.1.2 Effects of temperature.

Creep tests at constant temperatures, over a wide range of temperature levels, were conducted on small specimens in bending, compression and tension parallel and

perpendicular to the grain, shear, and torsion at various moisture contents, from green to oven-dry (Schniewind 1968).

The overall effect of temperature was an acceleration of creep with increasing temperature (Davidson 1962). Specifically, Bach (1965) reported that the tensile creep parallel to grain of hard maple was proportional to the square of the temperature in the range of 30^0C to 70^0C. Similarly, Kingston and Budgen (1972) and Kingston and Clarke (1961) found from bending and compression tests in the range of 20^0C to 50^0C that temperature had a significant effect on creep.

2.12.1.3 Effects of moisture.

Moisture in wood acts as a plasticizer; that is, creep increases with moisture content (Boyd and Jayne 1982; Schniewind 1968). This was observed in experiments with bending, torsion, tension and compression parallel and perpendicular to grain. For example, Bach (1965) deduced from tensile tests, with moisture contents in the range of 4% to 12%, that the creep compliance is proportional to the square of the moisture content. Moreover, the effect of moisture adsorbed below the fiber saturation point tends to be much greater on creep than on the initial deformation (Bodig, 1982).

Reviews on the effects of the interaction of moisture movement (drying and wetting) with the mechanical behavior of wood, called mechano-sorptive behavior (Grossman 1976), are provided by Schniewind (1968), Grossman et al. (1969), Grossman (1978), Johnson (1978), Bodig (1982). Early key papers on the subject were presented by Armstrong and Christensen (1961) and Hearmon and Paton (1964).

Experiments have demonstrated that changes in moisture content of the loaded specimen have a marked effect on the creep rate and the total creep. For example,Armstrong and Kingston (1960) observed that the relative creep of a loaded beam allowed to dry was at least twice that occurring in the loaded beam at constant moisture content.

2.12.1.4 Mechano-sorptive behavior

An important question for the designer is: to what extent can the mechano-sorptive behavior observed in the laboratory on very small specimens be realized by large structural members in the actual environment? Specifically, what is the effect of the range and period of the moisture content cycle and the size of the cross section on mechano-sorptive behavior? (Schniewind 1968).

The following researchers addressed this issue to some extent. Hearmon and Paton (1964) were interested in the relation between the increased deflection caused by moisture cycling and the range, the percent change, of the moisture content. They concluded that this relation appears to be linear. This suggests that a narrow range will result in a small increase in creep due to moisture cycling.

2.12.1.5 Mathematical Models for Creep in Wood

Several investigators have been concerned with the development of models to simulate mechano-sorptive behavior in wood: Leicester (1971) devised rheological models that include "mechano-sorptive elements" to fit experimental data. He proposed a

first approximation model for beam deflection, which was tested by Grossman (1971) who concluded it had value. Schaffer (1972) introduced a model to explain the change of creep response with changing moisture content by considering the effect of diffusion of moisture within the loaded specimen.

Ranta- Maunus (1975) expressed the creep strain arising from variations in moisture content in integral (hereditary) form on the basis of hydro-viscoelasticity theory. The model was applied to published experimental results.

Bazant (1985) proposed a speculative model of the effects of variations in moisture content and temperature on creep based on thermodynamics of the process of diffusion of water in wood. The model reflects qualitatively some experimental results. Quantitative fitting of test data was not attempted.

Mukudai and Yata (1986) proposed a model for viscoelastic behavior of wood under moisture change. Good agreement was observed between the model responses and published experimental results.

Schaffer (1982) was also concerned with the design of structural timber members to sustain loading during fire exposure. He developed a nonlinear (in stress) viscoelastic-plastic model based on thermodynamic constitutive theory (Schapery 1966). The model was correlated with experimental creep data, and Schaffer concluded that the resultant qualitative model sufficiently characterizes the viscoelastic- plastic response of dry wood parallel to the grain. Viscoelastic behavior of wood in changing environments is considered by Tang (1980).

2.12.2 Creep Rupture Modelling

Several models of load effect for timber and other materials can be found in the literature (Wood, 1951; Kohler and Svensson, 2002; Barret and Foschi, 1978; Ellingwood and Rosowsky, 1991; Foschi and Yao, 1986; Gerhards, 1979; Gerhards and Link, 1987; Hoffmeyer, 1990; Lindley, 1965; Madsen, 1992; Nielsen, 1979; Sorensen *et al*, 2001; Svensson *et al*, 1999).

Some of these have a conceptual framework from some physical mechanisms leading to failure over time as a background; others are just empirically derived to represent duration of load (DOL) test data. The modes can be divided into the following groups:

1. Empirical formulation for time to failure: The parameters of simple mathematical formulations are fitted to DOL test results. The Medison curve (Wood, 1951) was the earliest DOL model, formulated on the basis of results from laboratory tests on clear wood bending specimens, (that is specimens with no visible defects), exposed to loads of constant intensity.

   The aim of this model is to cover the effect of relatively long load duration and the effect of very short load duration. The Medison curve is an empirical curve describing the stress level ***sl***as a function of the time to failure. The curve is calibrated to three pre-selected points representing average values derived from several test programs

i. The short-term strength is defined as the failure load of a specimen loaded in a ramp load test with a corresponding average time to failure of 7.5 minutes, correspondingly, the stress level is 100% at 7.5 minutes (Wood, 1951).

ii. From impact loading tests it is found that the average stress level of ***sl*** of specimen loaded in a very fast ramp-load test of the duration of 0.015 second is 150%.

iii. From long-term loading tests it is found that the average stress level ***sl*** of specimen loading in a constant load test of the duration of 156 days is 66%.

The resulting curve was represented as:

$\boldsymbol{sl} = 90.4 - 6.3\log t_f$ (2.1)

Where ***sl*** is the stress level and t_f is the time to failure in hours.

2. Cumulative damage theories**:** A damage state variable without any precise physical definition was introduced. Empirical parameters were fitted to test results. The models and theoretical parameters are conditional on loading mode (Hoffmeyer, 1990).

   A major part of the model for describing the duration of load effect for timber involve a damage state variable to assess damage accumulation in timber structural members' subject to their loading histories. These models are referred to as damage accumulation models. In general, damage is expressed by a damage state variable α_0, where, $\alpha_0 = 0$ is equivalent with no damage and $\alpha_0 = 1$ is associated with full damage or failure (Hoffmeyer, 1990). Damage accumulation model are usually given as rate equation of damage over time $\frac{d\alpha_0}{dt}$, as:

$$\frac{d\alpha_0}{dt} = h(s(t), r_0, \theta)(for 0 \le \alpha_0 \le 1) \quad (2.2)$$

   Where h(.) is a function of the applied stress S(t), the short term strength r_0 and parameters θ.

The most prominent damage models are (Kohler and Svensson, 2002):

1. Gerhaard's Model (Gerhaards, 1979)
2. Foschi and Yao Model (Fosch and Yao, 1986)

The Gerhard's Model: The mathematical expression of Gerhard's model for calculating damage accumulation of a timber member with initial capacity, R_0 sustaining a load S(t), is given by the following equation.

$$\frac{d\alpha}{dt} = e^{(-a+b)\varsigma} \text{ for } 0 \le \alpha \le 1 \qquad (2.3)$$

where $\varsigma = \frac{S(t)}{R_0}$, α is the degree of damage (α = 0 denoting no damage and α = 1 denoting failure) a and b are model parameters.

Foschi and Yao Model: Equation 2.11 shows the mathematical expression of Foschi and Yao's model for calculating damage accumulation of a timber member with initial capacity, R_0 sustaining a load S(t).

$$\frac{d\alpha}{dt} = A\left(\frac{S(t)}{R_0} - \eta\right)^B + C\left(\frac{S(t)}{R_0} - \eta\right)^D \alpha(t) \text{ for } S(t) > \eta R \qquad (2.4)$$

$$\frac{d\alpha}{dt} = 0 \quad \text{for } S(t) \le \eta R_0 \qquad (2.5)$$

where A, B, C and D are model parameters to be calibrated from laboratory test data.

Fracture mechanics Model**:** Relative damage is defined as the growth of cracks. Model parameters have direct physical meaning. A model based on fracture mechanics was proposed by Nielsen (1979). The idea behind the 'Damaged Viscoelastic Material' (DVM) model is that structural timber may be seen as an initially damaged viscoelastic material, with the load-carrying capacity R_0 and where the damage is represented by cracks along the fibres.

The time-dependent behavior of timber under load is modeled by a single crack under stress perpendicular to the crack plane. For the case of a constant load level, S a damage accumulation law can be formulated from the DVM-model as (Hoffmeyer, 1990):

$$\frac{d\alpha}{dt} = \frac{\pi F L^2}{8q\tau}\alpha_k\left(\frac{S}{R_0}\right)^2\left[\left(\alpha_k - \left(\frac{S}{R_0}\right)^2\right)^{-1} - 1\right]^{(1/b)} \qquad (2.6)$$

where FL is the strength level defined as the ratio σ_{cr}/σ_i between the short term strength, σ_{cr} measured in a very fast ramp test and the intrinsic strength of the (hypothetical) non-cracked material σ_i (Hoffmeyer, 1990). The damage, α_k is defined as the ratio between the actual crack length, l, and the initial crack length l_0. $\alpha_k = 1$ corresponds to no damage and $\alpha_k = (S/R_0)^{-2}$ to full damage. T and b are creep material parameters. q is given as a function of creep exponent b and$q = (0.5(b+1)\ (b+2))^{(1/b)}$ and considers a parabolic increasing crack propagation.

2.12.3 Eurocode 5 Specification on Timber Deformation

Eurocode 5 (2004) recommends various limiting values of deflection for beams. The symbols relating to the deflection are shown in Figure 2.5. The code includes consideration for the load duration and moisture influences on deformations having time-dependent properties that is creep.

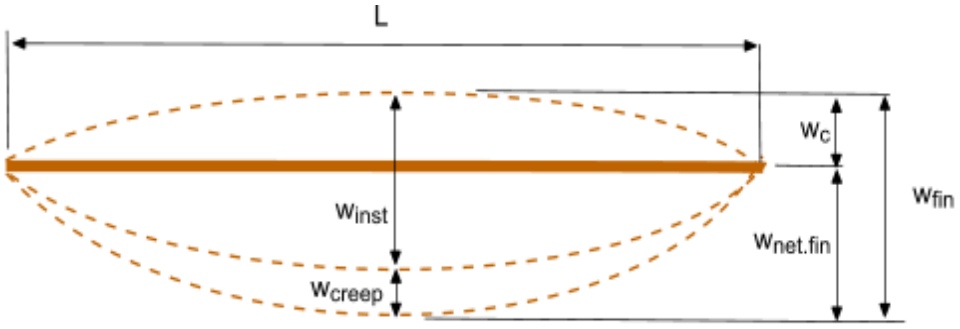

Figure 2.5: Deflection of beam according to Eurocode 5 (Eurocode 5, 2004)

Where w_{creep} is the creep deflection, w_c is the camber deflection, w_{inst} is the instantaneous deflection, $w_{net,fin}$ is the net final deflection due to permanent and variable actions = w_{fin} - wc, w_{fin} is the final deflection due to permanent and variable actions = $w_{inst} + w_{creep}$, u_m is the bending deflection and u_v is the shear deflection.

The final mean modulus of elasticity and shear modulus used to calculate deflections are obtained using the following equations. For Serviceability Limit State design

$$E_{mean,fin} = \frac{E_{mean}}{1 + k_{def}} \qquad (2.7)$$

$$G_{mean,fin} = \frac{G_{mean}}{1 + \psi_2 k_{def}} \qquad (2.8)$$

For Ultimate limit state design

$$E_{mean,fin} = \frac{E_{mean}}{1 + \psi_2 k_{def}} \qquad (2.9)$$

$$G_{mean,fin} = \frac{G_{mean}}{1 + \psi_2 k_{def}} \qquad (2.10)$$

Where k_{def} is a factor related to calculation of creep deformation, Ψ_2 is a factor for quasi-permanent value of the action causing largest stress (for permanent action this is 1).

2.13 Distributions Fitting and Tests of Goodness of Fit of the Measured Parameters

Material properties are random variables. Therefore, to effectively use timber as structural design there is the need to establish distribution models for each of the parameters. In that case, test of goodness of fit can be used to delineate the relative

degree of validity of the different distribution (Ang and Tang, 1975). Test of Goodness of Fit (GOF) may be undertaken using any of the following methods:

a) Anderson Darling test method

b) Chi-square test method

c) Kolmogorov Smirnov test method

Each of the three tests is used to test if a sample data came from a population with a specific distribution.

The Anderson darling has one major disadvantage that the critical value at a given significance level depends on the type of distribution being tested. This implied that critical values must be calculated for each distribution.

The chi-square distribution on the other hand requires a sufficient sample size in order for the chi-square approximation to be valid. The Kolmogorov smirnov test has the following two advantages over the Anderson darling and the Chi-square tests:

1) Kolmogorov smirnov test do not depend on the specific distribution being tested.
2) Kolmogorov smirnov test is an exact test. This has overcome the disadvantage of Chi-square test, in which sufficient sample size is required for the Chi-square approximation to be valid.

Kolmogorov Smirnov (K-S) test was adopted in this study. The test was performed on the density, modulus of elasticity and bending strength, of the *Terminalia ivorensis* (Black afara), in order to access if each data set comes from a population with a specific distribution. The basic procedure involves the comparison between the experimental cumulative frequency (Empirical Cumulative Distribution Function–ECDF) and the assigned theoretical distribution function. If the discrepancy is large with respect to what

is normally expected from a given sample size, the theoretical model is rejected (Ang and Tang, 1975).

The hypothesis is that "The data follow a specified distribution". The hypothesis regarding the distributional form is rejected if the test statistics, is greater than the critical value. The Kolmogorov Smirnov test of goodness of fit was implemented using Easyfit statistical package.

2.13.1 Probability Density Function

Probability density function (pdf) of random variable X, is the probability that a variate has a value x, given by:

$$F(x) = P(X = x) \qquad (2.11)$$

For a continuous distribution, the pdf of the random variable X, is expressed in terms of an integral between two points a and b:

$$\int_a^b f(x)dx = P(a \leq X \leq b) \qquad (2.12)$$

The empirical pdf for a given set of data is displayed as a histogram consisting of equal-width vertical bars, each representing the number of samples data value (falling into the corresponding interval divided by the total number of data points). The theoretical pdf is displayed as a continuous curve properly scaled depending on the number of intervals.

2.13.2 Distribution Models

Five commonly used distribution models were used in this studies for the Kolmogorov Smirnov test of goodness of fit, namely, normal distribution, lognormal distribution, gumbel distribution, frechet distribution and weibull distribution.

2.13.2.1 Normal Distribution

The normal distribution is the most widely known and used of all distributions. Because the normal distribution approximates many natural phenomena so well, it has developed into a standard of reference for many probability problems. Normal distribution had two parameters, mean (μ) and standard deviation (σ).

Normal distribution has the following characteristics:

a. Symmetric, bell shaped.
b. Continuous for all values of X between -∞ and ∞ so that each conceivable interval of real numbers has a probability other than zero.
c. $-\infty \leq X \leq \infty$
d. The distribution has two parameters, mean, μ and standard deviation. σ.
e. The probability density function of normal distribution is given by equation 2.13.

$$f(x;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\omega^2}} e^{-(x=-\mu)^2/2\sigma^2} \qquad (2.13)$$

f. The notation $N(\mu, \sigma^2)$ means normally distributed with mean μ and variance σ^2

2.13.2.2 Lognormal Distribution

A random variable X is said to have the lognormal distribution with parameters its mean, $\mu \in \mathbb{R}$ and standard deviation, $\sigma > 0$, if ln(X) has the normal distribution with mean

μ and standard deviation σ. The lognormal distribution is used to model continuous random quantities when the distribution is believed to be skewed.

The probability density function is defined by the mean μ and standard deviation, σ is given by equation 2.14.

$$N(\ln x;\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right],x>0 \qquad (2.14)$$

The shape of the lognormal distribution is defined by three parameters:

a. σ, the shape parameter. Also the standard deviation for the lognormal, this affects the general shape of the distribution. Usually, these parameters are known from historical data. Sometimes, you might be able to estimate it with current data. The shape parameter doesn't change the location or height of the graph; it just affects the overall shape.

b. m, the scale parameter (this is also the median). This parameter shrinks or stretches the graph.

c. Θ (or μ), the location parameter, which tells you where on the x-axis the graph is located.

2.13.2.3Gumbel Distribution

One of the first scientists to apply the theory was a German mathematician Emil Gumbel (1891-1966). Gumbel's focus was primarily on applications of extreme value theory to engineering problems. The Gumbel distribution, also known as the *Extreme Value Type I* distribution, is unbounded (defined on the entire real axis), with probability density function given by equation 2.15.

$$f(x)=\frac{1}{\sigma}\exp(-z-\exp(-z)) \qquad (2.15)$$

where z=(x-μ)/σ, μ is the location parameter, and σ is the distribution scale (σ>0). The probability density function plots for Gumbel distribution is shown on Figure 2.6.

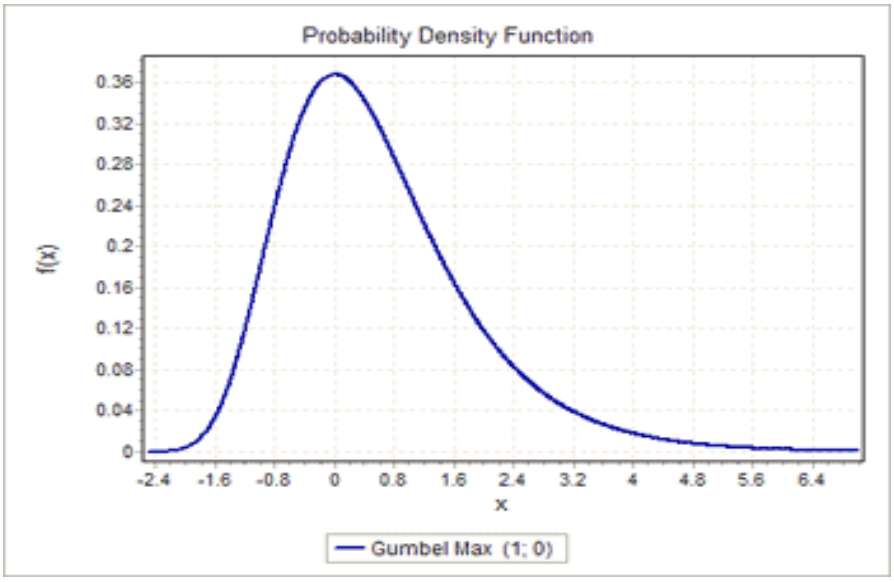

Figure 2.6: PDF of the Gumbel Distribution for σ=1 and μ=0.

2.13.2.4Frechet Distribution

Maurice Frechet (1878-1973) was a French mathematician who had identified one possible limit distribution for the largest order statistic in 1927. The Frechet distribution, also known as the *Extreme Value Type II* distribution, is defined by the probability density function given by equation 2.16.

$$f(x) = \frac{\alpha}{\beta}\frac{\beta}{x}^{\alpha+1} \exp\left(-\left(\frac{\beta}{x}\right)^{\alpha}\right) \qquad (2.16)$$

The probability density function plots for Frechet distribution is shown on Figure 2.7.

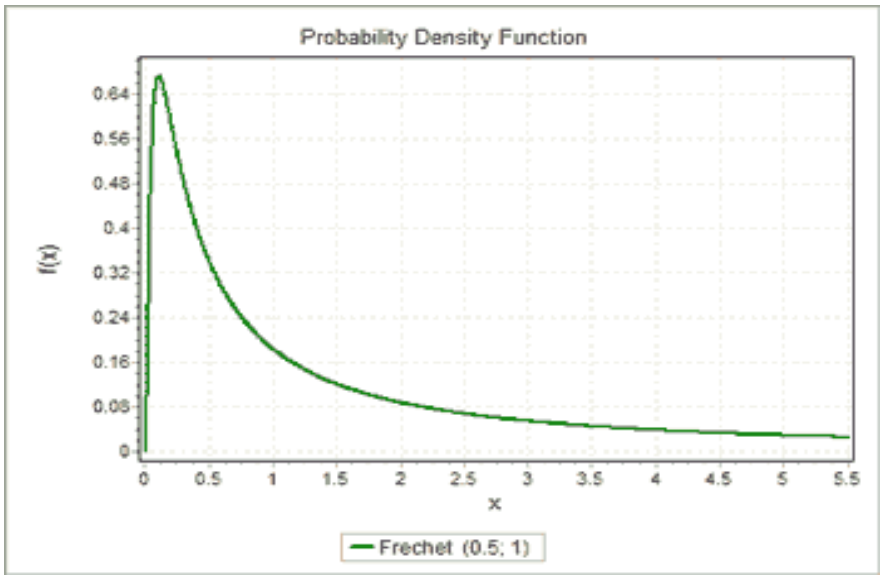

Figure 2.7: PDF of the Frechet Distribution for σ=1 and μ=0.

2.13.2.5 Weibull Distribution

Waloddi Weibull (1887-1979) was a Swedish engineer and scientist well-known for his work on strength of materials and fatigue analysis. The Weibull distribution, also known as the *Extreme Value Type III distribution*, first appeared in his papers in 1939. The two-parameter version of this distribution has the density function given by equation 2.17.

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\frac{x}{\beta}^{\alpha}\right) \tag{2.17}$$

The Weibull distribution is defined for x>0, and both distribution parameters (α - shape, β - scale) are positive. The two-parameter Weibull distribution can be generalized by adding the location (shift) parameter γ:

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\varepsilon-1} \exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right) \tag{2.18}$$

The probability density function plots for Weibull distribution is shown on Figure 2.8 below.

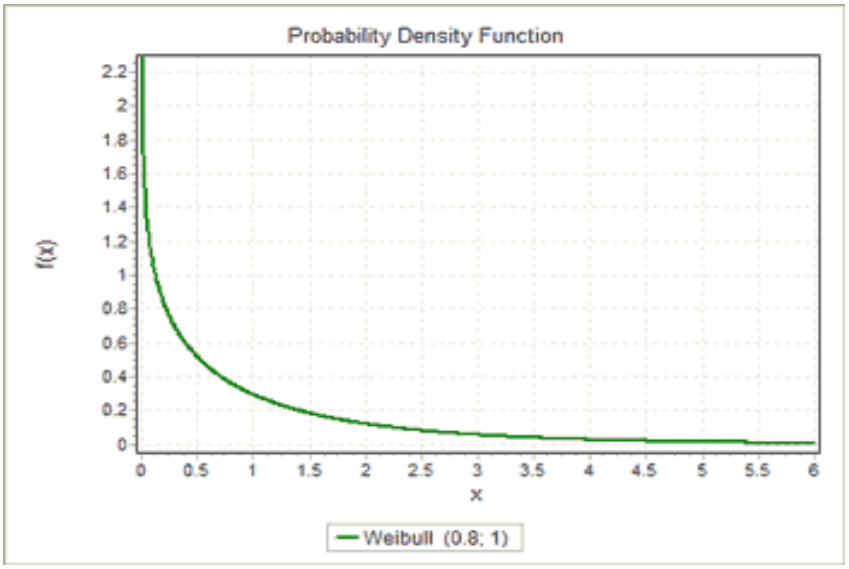

Figure 2.8: PDF of the Weibull Distribution for σ=1 and μ=0.

12.13.3Allocation of Strength Classes

The use of strength classes is intended to simplify the specification of timber, since it groups species in pre-defined categories. Characteristic values are taken from bending strength, bending stiffness and density of the timber and which depend on bending strength.

The allocation to a strength class is governed by the lowest strength class applicable to one of these properties. The classification of the species into various hardwood strength classes was made using the characteristic bending strength, mean value of density and mean values of modulus of elasticity based on the EN 338 strength classes. The limiting values of the reference material properties from EN 338 (2009) are presented in Table 3.1. For example, a timber specie is assigned to strength class D24, if

the characteristic value of bending strength, characteristic value of density and mean modulus of elasticity are greater than 18N/mm^2, 475kg/m^3 and 9.5kN/mm^2 and at least either the characteristic bending strength is less than or equal to 24N/mm^2, or the characteristic density is less than or equal to 485kg/m^3 or mean modulus of elasticity is less than or equal to 10kN/m^2.

12.13.4 Moisture Adjustment Factors

Most properties of timber vary with variation in moisture content below fibre saturation point (Ranta-Maunus, 2001). Following EN 384 (2004), Strength class values are derived from timber at about 12% moisture content, which is taken as reference moisture content. The test results in this study indicated that the equilibrium moisture contents of the species are above 12%. This is expected, because the reference moisture content specified in the Nigerian code of practice (NCP 2, 1973) is 18%. Therefore, adjustments to results are desirable. Prior to the assignment of the appropriate strength class to the *Terminalia ivorensis* timber specie, modulus of elasticity, bending strength and density values would be adjusted to 12% reference moisture content. (Kucera, 1992; Bostron, 1994; Heikkila and Hijarvi, 2008). Table 2.5 below shows the limiting values for the classification into hard wood classes in accordance to EN 338(2009).

Table 2.5: Limiting Values for Classification into Hardwood Classes (EN 338, 2009: Clause 5, Table 1)

S/No.	Strength Class	Limits of Characteristic Bending Strength (N/mm^2)	Limits of Characteristic Density (kg/m^3)	Limits of Mean Modulus of Elasticity (kN/mm^2)
1	D18	$f_{m,k} \leq 18$	$\rho_k \leq 475$	$E_{mean} \leq 9.5$
2	D24	$18 < f_{m,k} \leq 24$	$475 < \rho_k \leq 485$	$9.5 < E_{mean} \leq 10$
3	D30	$24 < f_{m,k} \leq 30$	$485 < \rho_k \leq 640$	$9.5 < E_{mean} \leq 10$
4	D35	$30 < f_{m,k} \leq 35$	$640 < \rho_k \leq 670$	$9.5 < E_{mean} \leq 10$
5	D40	$35 < f_{m,k} \leq 40$	$670 < \rho_k \leq 700$	$10 < E_{mean} \leq 11$
6	D50	$40 < f_{m,k} \leq 50$	$700 < \rho_k \leq 780$	$11 < E_{mean} \leq 14$
7	D60	$50 < f_{m,k} \leq 60$	$780 < \rho_k \leq 840$	$14 < E_{mean} \leq 17$
8	D70	$70 \leq f_{m,k}$	$1080 \leq \rho_k$	$20 \leq E_{mean}$

The 12% moisture content adjustment for bending strengthvalues would be adjusted to 12% reference moisture content using equation 2.19(Kucera, 1992; Bostron, 1994; Heikkila and Hijarvi, 2008).

$$f_{m,12\%} = \frac{f_{measured}}{1 - 0.0295(12 - u)} \qquad (2.19)$$

Where,

$f_{m,12\%}$ is the bending strength at 12% moisture content,

$f_{measured}$ is the bending strength at the measured moisture content,

u is the measured moisture content in %.

The 12% moisture content adjustment for modulus of elasticity values would be adjusted to 12% reference moisture content using equation 2.20(Kucera, 1992; Bostron, 1994; Heikkila and Hijarvi, 2008).

$$E_{m,12} = \frac{E_{measured}}{1 + 0.0143(12 - u)} \tag{2.20}$$

Where, $E_{m,12\%}$ is the bending strength at 12% moisture content,

$E_{measured}$ is the bending strength at the measured moisture content,

u is the measured moisture content in %.

Also the 12% moisture content adjustment for density is given by equation 2.21.

$$\rho_{12} = \rho_w \left(1 - \frac{0.5(u - 12)}{100}\right) \tag{2.21}$$

Where ρ_{12} is the density at 12% moisture content, ρ_w is the density at measured and u is the measured moisture content in %.

The reference material properties would also be adjusted to Nigerian standard moisture content (NCP 2, 1973) of 18%, using linear interpolation on Microsoft Excel platform, using the measured data and 12% moisture content based values.

2.14 Microstructure and Chemistry of Wood

The wood cell contains three polymers: cellulose, hemicellulose, and lignin. Cellulose, the primary constituent, is arranged in microfibrils. Lignin and hemicellulose serve as the matrix to bind the fibrils together.

Although the polymer composite is complex, it obeys general polymer physics principles. Thus it is anticipatedthat to a certain extent, concepts such as time-temperature superposition will be applicable, if only in a thermo-rheologically complex sense.

Although one can conduct phenomenological rheology studies to curve fit rather arbitrary mathematical models to experimental data, the insights gained into long-term prediction capabilities and justification cannot be as great as could be derived from a molecular rheology approach (Pentoney and Davidson 1962). The unique cellular microstructure of wood suggests reasons for observed behavior. For example, the creep of wood in shear is less than the creep perpendicular to the grain (Schniewind and Barrett 1972).

This is exactly opposite the measured behavior in man-made fiber reinforced plastics, but it can be explained by the cellular honeycomb-like microstructure of wood. An understanding of the microstructure and its variability can provide valuable insight into wood behavior. Although polymeric and microstructural aspects are essential guiding concepts, constitutive relations at the continuum level are the essential building blocks for modeling the behavior of a structural element. Of particular interest for skeletal structures are the tensile and compressive properties in the longitudinal direction and the shear behavior.

2.14.1 Microstructural Analysis

Microstructural analysis of sample is usually obtained using scanning electron microscope. A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography and composition.

The scanning electron microscope (SEM) is one of the most versatile instruments available for the examination and analysis of the microstructural characteristics of solid

objects (Kamran, 1997). The primary reason for the SEM's usefulness is the high resolution that can be obtained when bulk objects are examined; values on the order of 2 to 5 nm (20-50 Å) are now usually quoted for commercial instruments, while advanced research instruments are available that have achieved resolutions of better than 1 nm (10Å).

Scanning electron microscopy is considered an important tool for observing the morphological characteristics of degraded wood at the level of cell wall, evaluating their damage, and identifying the causal agent of decay patterns. Methods for characterizing surface properties of wood may be divided into three broad categories: microscopic, spectroscopic, and thermodynamic (Schniewind 1968).

Microscopic methods provide information about surface morphology; spectroscopic methods provide information about its chemistry; and thermodynamic methods provide information about the surface energy. Many types of microscopic methods are available for characterizing the physical properties of various material surfaces, but only a few have been particularly useful for characterizing the physical properties of wood surfaces such as scanning electron microscopy (SEM) (Wells, 1974).

Furthermore, the use of the scanning electron microscope for the study of the structure of wood under stress and the mechanism of its cohesive failure can supply information which seems to be unobtainable by any other method (Kretschmann and Bendtsen, 1992).

In addition, SEM have proven to give a lot of information not only about the morphological changes of archaeological wood, but also about the elemental composition of the different layers that were used to cover and decorate wood in the past.

The electron microscope was apparently first used by Eitel (1941, 1942), and by Radczewski et al. (1939) to study the hydration process of concrete. Grudemo (1960) was another important pioneer in the use of high magnification, including the use of the electron microscope. Although most of these studies were not directly related to cracks, they led the way to later studies of cracks in which electron microscopy was a powerful tool. Diamond and Mindess (1980) used the scanning electron microscope to observe the growth of surface cracks during loading, using magnifications generally from 35X to 450X.

Le Chattelier (1882) was amongst the first to apply the microscope to the study of cementitious materials. He used it to investigate the chemical and physical aspects of hydration and setting, rather than to study cracks. His efforts undoubtedly influenced later workers in their use of the microscope as it has been a powerful tool in the study of cement and concrete. Tavasci (1942) successfully used the microscope to study the composition and structure of concrete, but not for cracks per se. His work, however, set the stage for the studies of cracks on the interior surfaces of cut specimens which were conducted in the 1960s.

In the work of Tripati *et al.,* (2016), SEM was carried out on Teak (*Tectona grandis*): a preferred timber for shipbuilding in India as evidenced from shipwrecks, to differentiate the type of timber and its distinctive features depending on whether it belongs to the hardwood or softwood group. It was also done to show the differences that exist in their anatomical structure and show a remarkably wide range of variations in physical and mechanical properties such as colour, texture, grain, density, strength, stiffness, hardness, etc.

The variations in the microstructure of different wood species was found to mostly depend on the proportions, size and distribution of various cell types such as vessels, fibres, parenchyma, rays, including gum canals, ripple marks, etc. Based on internal structure, properties and performance, timber is put to a variety of uses (Tripati *et al*, 2016).

Also, while studying Mechanical Deterioration in an archeological wood, Borgin (1971) studied the mechanism of fracture and cohesive failure of the structure of wood and gave the following results: cohesive failure when the wood was exposed to shear along the grain and tension across the grain, showed clearly that the weakest part of the ultrastructure of wood under such conditions was the bonds between parallel strands of microfibrils which were pulled out with little resistance from the matrix.

However, the adhesion between the middle lamella and the cell wall or the middle lamella itself failed when the wood was exposed to cleavage parallel to the grain. Loads and stresses caused mechanical damage to the wood cell walls where separations within the secondary walls and fractures in middle lamellae can be observed especially in the large wooden objects and structural wooden elements (Blanchette *et al.,* 1994). In cases where weak wood is exposed to heavy loads the cell walls collapse (El Hadidi, 2005). Internal stresses caused by expansion or contraction of wood due to gain or loss of moisture can be obvious while studying samples using SEM. The cells take the same curvature as that of the warped wood (El Hadidi, 2006).

Borgin (1970) used the scanning electron microscope to study the changes in the structure and ultrastructure of wood exposed to natural weathering for several hundred years. The result revealed in detail the mechanism of the structural breakdown, and

illustrated the gradual, very slow deterioration and ultimate destruction of the middle lamella, the various cell-wall layers, the separation of fibers and bundles of microfibrils from the surface and the enlargement of bordered pits and other pores. It also showed that these processes were confined to the surface layer (2-3 mm) and that most cell walls on exposed transverse surfaces are separated at the middle lamella region, apparently because of the degradation of lignin.

Owen et al., 1993 revealed that degradation caused by the full weathering process, comprising both water and ultra violet light, is considerably more rapid and more extensive than exposure to any parameter individually. SEM data, however, show that water has a deleterious effect on the physical characteristics of the surface. The swelling effect of water on wood, however, was detected clearly by SEM but not by infrared spectroscopy.

2.14.2 Chemical Components of the Wood

2.14.2.1 Carbohydrates

The carbohydrate portion of wood comprises cellulose and the hemicelluloses.

i. Cellulose content ranges from 40 to 50% of the dry wood weight, and hemicelluloses range from 25 to 35%. Cellulose is a glucan polymer consisting of linear chains of 1,4-β-bonded anhydroglucose units. (The notation 1,4-β describes the bond linkage and the configuration of the oxygen atom between adjacent glucose units.) Figure 2.6 shows a structural diagram of a portion of a glucan chain. The number of sugar units in one molecular chain is referred to as the degree of polymerization (DP). Even the most

uniform sample has molecular chains with slightly different DP values. The average DP for the molecular chains in a given sample is designated by $\overline{DP}$.

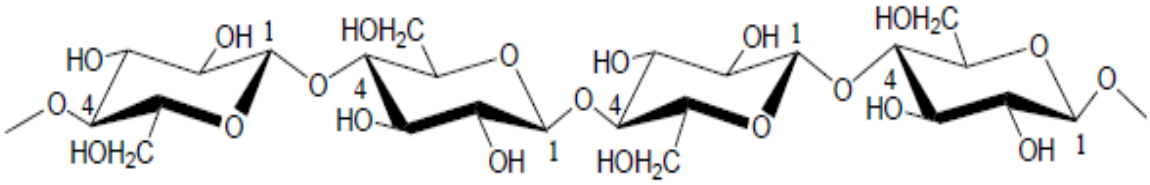

Figure 2.9: The structure of cellulose (Klemn *et al.,* 2005)

ii. Hemicelluloses are mixtures of polysaccharides synthesized in wood almost entirely from glucose, mannose, galactose, xylose, arabinose, 4-O methylglucuronic acid, and galacturonic acid residues. Some hardwoods contain trace amounts of rhamnose. Generally, hemicelluloses are of much lower molecular weight than cellulose and some are branched. They are intimately associated with cellulose and appear to contribute as a structural component in the plant. Some hemicelluloses are present in abnormally large amounts when the plant is under stress; e.g., compression wood has a higher than normal galactose content as well as a higher lignin content (Horii et al., 1987). Hemicelluloses are soluble in alkali and easily hydrolyzed by acids.

2.14.2.2 Lignin

Lignin is a phenolic substance consisting of an irregular array of variously bonded hydroxy- and methoxy-substituted phenylpropane units. The precursors of lignin biosynthesis are p-coumaryl alcohol (I), coniferyl alcohol (II), and sinapyl alcohol (III). I

is a minor precursor of softwood and hardwood lignins; II is the predominant precursor of softwood lignin; and II and III are both precursors of hardwood lignin (Klemn *et al.*, 2005). These alcohols are linked in lignin by ether and carbon–carbon bonds. Figure 2.9 (Klemn *et al.*, 2005) is a schematic structure of a softwood lignin meant to illustrate the variety of structural components. The 3,5-dimethoxy-substituted aromatic ring number 13 originates from sinapyl alcohol, III, and is present only in trace amounts (<1%) (Sjostrom, 1993). Figure 2.7 does not show a lignin-carbohydrate covalent bond. There has been much controversy concerning the existence of this bond, but evidence has been accumulating in its support (Sjostrom, 1993; Klemn *et al.*, 2005).

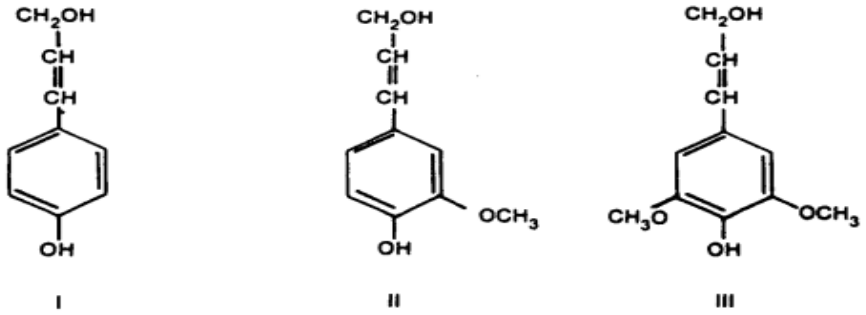

Figure 2.10: Wood Lignin (Klemn *et al.*, 2005).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Preamble

Reliable information regarding the strength and stiffness of timber in Nigeria, is one of the major obstacles to their use in building construction application, based on the requirements of the EN 338 and Eurocode 5 (Kaura, 2014).

The allocation of specie to a particular strength class based on EN 338(2009), allows engineers to use the mechanical properties of the strength class in limit state design of timber structures based on the Eurocode 5 (2004) specification. One of the objectives of this research is to establish the strength and stiffness properties of the Nigerian, *Terminalia ivorensis* (Black afara) timber specie.

The strengths properties of interest are bending strength, compression strength parallel and perpendicular to grain, tension strength parallel and perpendicular to grain and shear strength. The stiffness properties include modulus of elasticity and shear modulus. The density and moisture content of the timber species would also be established.

The material properties of timber are classified into two; reference properties and other properties. The reference properties include density, bending strength and modulus of elasticity. The other properties such as the tension and compression strengths parallel and perpendicular to grain, shear strength and shear modulus are derived from the reference material properties.

Therefore, the only properties that were determined from the laboratory are the reference properties, and the other properties were determined using empirical models given in EN 384 (2004) and JCSS (2006). The material properties were then used to assign the timber specie to the appropriate strength grade (class) according to EN 338 (2009).

The research also includes the establishment of the stochastic model of each property; mean values, coefficient of variation and theoretical distribution models for used in structural reliability analysis.

3.2 Materials

The material used in this study is *Terminaliaivorensis* (Black afara) timber, obtained from the Sabon Gari Zaria timber market (Zaria timber sheds). This specie was chosen to reflect the current trends in wood usage of timber in Nigeria. *Terminalia ivorensis* is used extensively as timber for many structural applications especially for roof truss fabrication. The *Terminalia ivoresnsis* timber specimen were prepared for the various tests and delivered at the structures and material laboratory of the Department of Civil Engineering, Ahmadu Bello University, Zaria, on 10th January, 2014. After the delivery at the laboratory, the timberwas conditioned to (20±2) ^{0}C and (65±5) % relative humidity, prior to testing based on EN 384 (2004) specification. Testing commenced at the laboratory on 12th April, 2015.

3.3 Methods of Test

The following section provides explanations on the test procedures, methods and specifications adopted in carrying out testing of Terminalia ivorensis in the study.

3.3.1 Determination of Density and Moisture Content

The test specimens for the density and moisture content tests were prepared as specified in EN 13183-1 (2002). Forty specimens of dimension 40mm x 40mm x 70mm were prepared. The specimens were labelled A-1, A-2, A-3, A-4… A-40 for the density test, $\rho_d$andB-1, B-2, B-3, B-4… B-40 for moisture content. According to EN 13183-1 (2002), the formulae for calculating density and moisture content are given in equation 3.1 to 3.3below.

$$\rho_b = \frac{m_u}{V} \qquad (3.1)$$

Where;

ρ_b= bulk density in kg/m^3

m_u = bulk mass in kg

V = volume of sample in m^3

$$\rho_d = \frac{m_o}{V} \qquad (3.2)$$

ρ_d = dry density in kg/m^3

m_o = oven dry mass in kg

V = volume of sample in m^3

$$mc\ (\%) = \frac{m_u - m_0}{m_0} x100 \qquad (3.3)$$

The terms defined in equations 3.1 and 3.2 are same for 3.3

The actual prepared dimensions of each of the forty specimens were measured with a Vernier caliper and presented in appendix A.

Consideringthe first specimen A-1 has the following measured parameters:

Depth (h) = 76mm; Thickness (t) = 50mm; Width (b) = 46mm; bulk mass (m_b) = 102g;oven-dry mass (m_0) = 87.8g.

The density and the moisture contents were determined using equations 3.2 and 3.3 respectively as follows;

Density = $\frac{87.8\ x\ 10^{-3}}{76\ x\ 50\ x\ 46\ x\ 10^{-9}} = 502.3\ kg/m^3$

Moisture content = $\left(\frac{102 - 87.8}{87.8}\right)x100$ = 16.18%

Similarly, density and moisture content for all the samples were calculated and is as shown in tables 3.1 and 3.2 below.

Table 3.1: Density of the *Terminalia ivorensis*

S/No	Sample No	Oven Dry Weight (g)	Dimension (mm)			Volume (mm^3)	Density (kg/m^3)
			Depth	Thickness	Width		
1	A-1	87.8	76	50	46	174800	502.3
2	A-2	68.3	75	49	52	191100	356.4
3	A-3	63.0	75	49	43	158025	392.3
4	A-4	57.5	70	51	31	110670	514.2
5	A-5	73.9	72	50	47	169200	434.7
6	A-6	71.6	70	52	40	145600	499.0
7	A-7	74.4	74	50	51	188700	400.3
8	A-8	71.8	72	50	48	172800	415.5
9	A-9	67.1	74	51	37	139638	485.6

10	A-10	61.0	71	49	30	104370	577.7
11	A-11	73.9	74	49	42	152292	484.6
12	A-12	87.4	70	49	52	178360	489.1
13	A-13	58.0	77	50	37	142450	401.0
14	A-14	89.3	72	49	61	215208	413.3
15	A-15	76.5	73	49	55	196735	384.2
16	A-16	68.8	77	51	45	176715	390.9

Table 3.1: Density of the *Terminalia ivorensis* (Continued)

S/No	Sample No	Oven Dry Weight (g)	Dimension (mm)			Volume (mm^3)	Density (kg/m^3)
			Depth	Thickness	Width		
17	A-17	91.4	78	50	51	198900	461.4
18	A-18	73.6	77	51	35	137445	536.8
19	A-19	55.4	79	50	37	146150	382.8
20	A-20	61.3	77	51	35	137445	453.6
21	A-21	72.1	78	51	35	139230	517.8
22	A-22	64.0	75	50	53	198750	322.7
23	A-23	93.2	78	50	50	195000	477.6
24	A-24	91.4	76	49	70	260680	347.4
25	A-25	67.0	71	50	44	156200	433.7
26	A-26	70.6	74	51	42	158508	447.0
27	A-27	61.2	79	51	38	153102	395.7
28	A-28	78.0	73	50	45	164250	470.6
29	A-29	73.6	82	51	40	167280	433.4
30	A-30	67.8	76	51	34	131784	525.9
31	A-31	63.4	77	48	38	140448	451.9
32	A-32	65.7	73	50	29	105850	610.1
33	A-33	76.9	72	50	39	140400	547.2

34	A-34	77.3	71	50	53	188150	406.3
35	A-35	80.6	74	49	51	184926	437.6
36	A-36	69.0	75	51	40	153000	456.7
37	A-37	55.0	74	50	44	162800	344.6
38	A-38	77.5	78	49	64	244608	316.7
39	A-39	77.6	80	51	40	163200	474.8
40	A-40	73.1	68	51	41	142188	514.4

Table 3.2: Moisture Content of *Terminalia ivorensis*

S/No	Sample No	Bulk Weight (g)	Oven Dry Weight (g)	Moisture Content (%)
1	B-1	102.0	87.8	16.2
2	B-2	77.9	68.3	14.2
3	B-3	72.8	63.0	15.5
4	B-4	64.4	57.5	12.1
5	B-5	86.4	73.9	16.9
6	B-6	80.4	71.6	12.3
7	B-7	87.0	74.4	16.8
8	B-8	87.2	71.8	21.4
9	B-9	79.6	67.1	18.6
10	B-10	73.4	61.0	20.4
11	B-11	84.5	73.9	14.3
12	B-12	104.8	87.4	19.9
13	B-13	68.7	58.0	18.5
14	B-14	103.5	89.3	15.8
15	B-15	88.5	76.5	15.6
16	B-16	85.3	68.8	24.0
17	B-17	105.7	91.4	15.7

18	B-18	86.2	73.6	17.1
19	B-19	65.2	55.4	17.7
20	B-20	72.1	61.3	17.5

Table 3.2: Moisture Content of *Terminalia ivorensis* (Continued)

S/No	Sample No	Bulk Weight (g)	Oven Dry Weight (g)	Moisture Content (%)
21	B-21	89.8	72.1	24.6
22	B-22	80.5	64.0	25.8
23	B-23	112.4	93.2	20.6
24	B-24	114.4	91.4	25.2
25	B-25	83.8	67.0	25.1
26	B-26	82.2	70.6	16.5
27	B-27	71.6	61.2	17.0
28	B-28	90.6	78.0	16.2
29	B-29	88.0	73.6	19.7
30	B-30	78.7	67.8	16.0
31	B-31	73.2	63.4	15.5
32	B-32	78.6	65.7	19.7
33	B-33	95.0	76.9	23.5
34	B-34	91.7	77.3	18.6
35	B-35	95.2	80.6	18.1
36	B-36	78.5	69.0	13.7

37	B-37	64.8	55.0	17.8
38	B-38	84.9	77.5	9.4
39	B-39	92.6	77.6	19.4
40	B-40	81.6	73.1	11.6

3.3.2 The Bending Test

The determination of global modulus of elasticity of timber using four-point bending test, is based on the application of loading at the central third of the test piece. Local Modulus of Elasticity was first recommended in the previous edition of EN 408 (EN 408, 1995).

This method for the determination of local modulus of elasticity do not give consistent and reliable results (Kaura, 2014), because the determination of the MOE is based on measurement of a deflection over a relatively short span between the loading point. The deflections are small, often less than 1 mm. Hence the method is sensitive to measurement errors. Such errors can be caused by twisting of the timber during the test (Kaura, 2014).

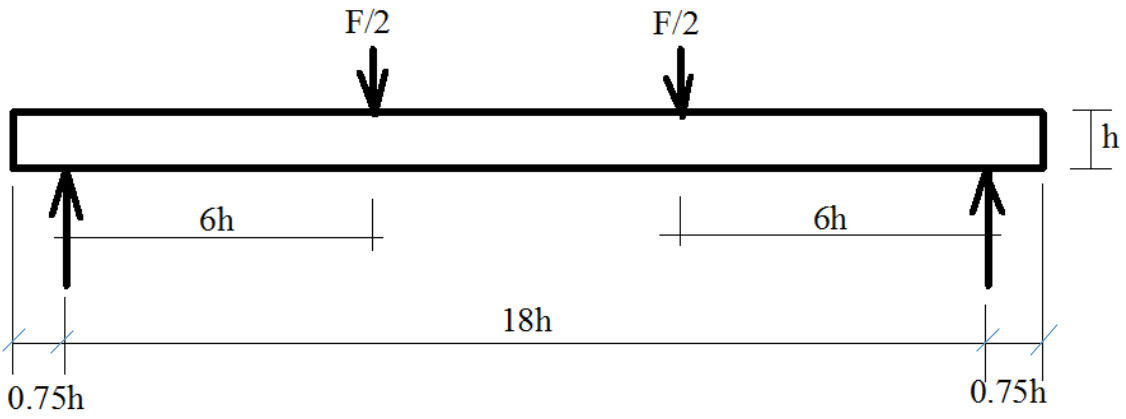

Figure 3.1: Four-point bending test set-up (EN 408, 2004).

In EN 408, (2004), the global modulus of elasticity is calculated from the measured samples as;

$$E_m = \frac{L^3(F_2 - F_1)}{4.7bh^3(w_2 - w_1)} \qquad = \frac{L^3\ \Delta F}{4.7\ b\ h^3 \Delta w} \tag{3.4}$$

Where:

L = the centre to centre distance between supports in mm,

b = the width of the specimen in mm,

h = the depth of the specimen in mm,

F_2-F_1 = ΔF = the increment of load in N

w_2-w_1 = Δw = corresponding increment deformation in mm

And the bending Strengths as;

$$f_m = \frac{a F_{max}}{2W} \tag{3.5}$$

Where;

a = the distance between any one support and the load that is closer to the support in mm

F_{max} = the failure load, and

W = the section modulus of the specimen in mm^3.

Considering test data forspecimen C-1 is as follows:

a = 400mm b = 50mm

L = 1200mm h = 75mm

and being loaded at F = 2000N, 3000N, 4000N and 5000N. The central deflection at the load points are 3.4mm, 5.3mm 5.9mm and 6.5mm respectively. Thus, the global modulus of elasticity is given by

$$E_m = \frac{1200^3 x 915,4}{4.7 x 50 x 75^3} = 15955.23 \text{N/mm}^2$$

Note: $\frac{\Delta F}{\Delta W}$ = Slope of the linear portion of load deformation curves plotted using the load deformation data obtained from bending test.

Slope for each of the test specimen was determined using regression analysis (Microsoft excel) for the forty samples and presented in Appendix B. The slope of sample C-1 is 915.4.

Thus, all global modulus of elasticity obtained and as shown in table 3.3 below

Table 3.3: Global Modulus of Elasticity of Terminalia Ivorensis Timber Samples

S/No	Sample No	Deflection (mm)				Gradient	Global Modulus of Elasticity (N/mm^2)
		2000 (N)	3000 (N)	4000 (N)	5000 (N)		
1	C-1	3.4	5.3	5.9	6.5	915.4	15955.23
2	C-2	3.5	5.5	6.2	6.8	857.6	14947.8
3	C-3	3.1	4.8	5.3	5.9	1023.0	17830.7
4	C-4	3.7	5.2	5.7	6.3	1119.0	19503.9
5	C-5	3.3	5.5	6.2	6.9	789.0	13752.1
6	C-6	3.8	6.1	6.9	7.6	745.7	12997.39
7	C-7	3.3	5.4	6.1	6.8	816.3	14227.94
8	C-8	3.9	5.2	5.6	6.1	1315.0	22920.17
9	C-9	2.9	4.4	4.9	5.4	1142.0	19904.82
10	C-10	3.0	4.6	5.1	5.7	1069.0	18632.44
11	C-11	3.7	5.2	5.7	6.2	1142.0	19904.8

12	C-12	3.3	4.7	5.2	5.7	1200.0	20915.7
13	C-13	3.2	5.2	5.9	6.5	857.6	14947.8
14	C-14	3.5	6.6	7.7	8.7	548.3	9556.8
15	C-15	2.7	4.1	4.6	5.1	1200.0	20915.7
16	C-16	2.7	4.9	5.6	6.3	789.0	13752.1
17	C-17	3.7	5.1	5.5	6.0	1246.0	21717.51
18	C-18	2.9	4.8	5.5	6.2	876.0	15268.49
19	C-19	4.0	6.4	7.2	8.0	714.2	12448.35

Table 3.3: Global Modulus of Elasticity of Terminalia Ivorensis (Continued)

S/No	Sample No	Deflection (mm)				Gradient	Global Modulus of Elasticity (N/mm^2)
		2000 (N)	3000 (N)	4000 (N)	5000 (N)		
20	C-20	3.1	5.1	5.8	6.4	857.6	14947.79
21	C-21	2.3	4.1	4.6	5.2	980.8	17095.1
22	C-22	4.3	6.6	7.3	8.1	753.6	13135.1
23	C-23	4.5	5.9	6.3	6.8	1246.0	21717.5
24	C-24	3.0	5.1	5.8	6.4	827.3	14419.7
25	C-25	3.3	4.7	5.2	5.6	1225.0	21351.5
26	C-26	2.4	4.3	4.9	5.5	915.0	15948.26
27	C-27	3.9	6.2	7.0	7.7	745.7	12997.39
28	C-28	2.3	3.9	4.5	5.0	1053.0	18353.57
29	C-29	3.6	5.9	6.7	7.5	736.3	12833.55
30	C-30	3.1	5.0	5.6	6.2	915.4	15955.23
31	C-31	4.2	5.8	6.4	7.0	1034.0	18022.4
32	C-32	3.2	5.5	6.3	7.0	745.7	12997.4

33	C-33	3.4	5.1	5.6	6.2	1023.0	17830.7
34	C-34	3.2	5.0	5.6	6.1	967.2	16858.1
35	C-35	2.5	5.5	6.6	7.6	561.2	9781.597
36	C-36	3.5	6.9	8.0	9.1	508.3	8859.561
37	C-37	2.8	4.9	5.6	6.3	816.3	14227.94
38	C-38	4.1	5.9	6.5	7.1	952.3	16598.39
39	C-39	3.6	5.5	6.1	6.8	901.0	15704.24
40	C-40	2.6	4.4	4.9	5.5	980.8	17095.14

Table 3.4: Bending Strength of Terminalia Ivorensis Timber Samples

S/No	Sample No	Failure Load (kN)	Section Modulus (mm^3)	Bending Strength (N/mm^2)
1	D-1	14.1	46875.0	60.34
2	D-2	18.4	46875.0	78.36
3	D-3	16.8	46875.0	71.59
4	D-4	14.0	46875.0	59.70
5	D-5	17.6	46875.0	75.27
6	D-6	24.1	46875.0	102.76
7	D-7	20.5	46875.0	87.56
8	D-8	19.1	46875.0	81.32
9	D-9	18.5	46875.0	78.91
10	D-10	21.7	46875.0	92.52
11	D-11	20.4	46875.0	87.03
12	D-12	20.8	46875.0	88.61
13	D-13	14.9	46875.0	63.51

14	D-14	16.4	46875.0	70.14
15	D-15	24.6	46875.0	104.92
16	D-16	22.9	46875.0	97.71
17	D-17	17.5	46875.0	74.66
18	D-18	21.1	46875.0	89.92
19	D-19	20.4	46875.0	87.03
20	D-20	24.8	46875.0	105.66

Table 3.4: Bending Strength of Terminalia Ivorensis Timber Samples (Contd.)

S/No	Sample No	Failure Load (kN)	Section Modulus (mm^3)	Bending Strength (N/mm^2)
21	D-21	19.3	46875.0	82.14
22	D-22	21.2	46875.0	90.38
23	D-23	14.2	46875.0	60.80
24	D-24	16.7	46875.0	71.14
25	D-25	17.6	46875.0	75.30
26	D-26	17.9	46875.0	76.25
27	D-27	21.6	46875.0	91.96
28	D-28	15.2	46875.0	64.74
29	D-29	18.2	46875.0	77.52
30	D-30	12.2	46875.0	51.95
31	D-31	16.3	46875.0	69.50
32	D-32	18.0	46875.0	76.94
33	D-33	21.2	46875.0	90.47

34	D-34	22.8	46875.0	97.21
35	D-35	21.2	46875.0	90.39
36	D-36	17.0	46875.0	72.75
37	D-37	17.6	46875.0	75.18
38	D-38	20.4	46875.0	87.11
39	D-39	21.0	46875.0	89.58
40	D-40	21.8	46875.0	93.08

Similarly, the bending strength of sample D-1 is obtained thus using equation 3.5.

$$f_m = \frac{a F_{max}}{2W} = \frac{400\ x\ 14100}{2\ x\ 46875} = 60.34 \text{N/mm}^2$$

The bending strength for the forty samples are as shown in table 3.4 below.

3.3.3 Creep Deformation Tests

All materials undergo deformation when subjected to loading.The deformation is a gradual process under constant load and accumulates with time into a large deformation usually referred to as creep. In this study, the DIN 50119 (1978), a German code of practice that deals with creep is used to measure the time-dependent deformation of Terminalia ivorensis timber. A machine called the TONI.MFL PRUFSYSTEME creep testing machine as shown in Plate 3.1 was used for the experimental work. It keeps the sample under constant stress by a nitrogen tank of 96 bars (960kN) maximum test force. The samples are placedin between top plate and base plate mounted on spring with oil pot

as seen in plate 3.1 below. The magnitude of the load applied on the sampleis one-third the specimen compressive strength as specified by the code.

Plate I: Set-up of Creep Testing Machine

Three specimen, 165mm x 150mm x 145mm (for sample A), 154mm x 145mm x 150mm (for sample B) and 165mm x 150mm x 145mm (for sample C) were prepared for creep testing. To measure the creep deformation, dial gauges were mounted on both sides

of the sensitive spring of the equipment which is always in constant touch with the specimen flat surfaces at ninety degrees.

All the three samples were loaded and readings were taken in hours, days, months, up to one year. The readings are as shown in tables 3.5, 3.6 and 3.7 below.

Table 3.5: Creep Reading for Sample A

S/No	Load duration time (Days)	Creep deformation (x 10^{-2}mm) for Sample A
1	0	0.000
2	1	0.825
3	2	0.835
4	3	0.825
5	4	0.825
6	5	0.852
7	6	0.857
8	7	0.870
9	14	1.022
10	21	1.332
11	28	1.367
12	30	1.392
13	60	1.424
14	90	1.442
15	120	1.469
16	150	1.537
17	180	1.564
18	210	1.557
19	240	1.591
20	270	1.652
21	300	1.632

22	330	1.662
23	360	1.629

Table 3.6: Creep Reading for Sample B

S/No	Load duration time (Days)	Creep deformation (x 10^{-2}mm) for Sample B
1	0	0.000
2	1	0.457
3	2	0.465
4	3	0.465
5	4	0.468
6	5	0.468
7	6	0.468
8	7	0.468
9	14	0.474
10	21	0.531
11	28	0.536
12	30	0.538
13	60	0.543
14	90	0.551
15	120	0.556
16	150	0.559
17	180	0.560
18	210	0.562
19	240	0.562
20	270	0.565
21	300	0.566
22	330	0.568
23	360	0.566

Table 3.7: Creep Reading for Sample C

S/No	Load duration time (Days)	Creep deformation (x 10^{-2}mm)for Sample C
1	0	0.000
2	1	0.348
3	2	0.348
4	3	0.348
5	4	0.350
6	5	0.352
7	6	0.353
8	7	0.351
9	14	0.348
10	21	0.355
11	28	0.360
12	30	0.361
13	60	0.366
14	90	0.371
15	120	0.371
16	150	0.376
17	180	0.376
18	210	0.377
19	240	0.381
20	270	0.384
21	300	0.387
22	330	0.388
23	360	0.386

3.3.4 Microstructure Analysis of Terminalia Ivorensis

In themicrostructure of Terminalia ivorensis, four sample were prepared**.** Two specimens were tested; one before creep and one after creep. The size of each sample is 2mm x 2mm.

Scanning Electron Microscope with model number MVE 016477830 was used to carry out the Scanning Electron Microscopy (SEM) in Department of Chemical Engineering, Ahmadu Bello University, Zaria. For each test, a piece of the timber specimen is placed on a sample stub. A carbon double adhesive was placed on the sample stub and then charged into the sputter coater. A five nanometer of gold was deposited on the sample to make it conductive.A sample holder was used to hold the sample and introduced into the column of SEM machine, where it was viewed with a navigation camera for proper focusing, brightness and contrasting. This was then transferred into SEM mode where different magnifications saved via a USB stick.

CHAPTER FOUR

ANALYSIS OF RESULTS AND DISCUSSIONS

4.1 Preamble

In this chapter, the measured global modulus of elasticity, moisture content, density and bending strength were used as base line data and other properties of *Terminalia Ivorensis* timber are analyzed and calculated to determine its properties values. These values are tested for distribution fitting and goodness of fit to know the statistical distribution model and values necessary for use in engineering reliability design. Also, creep deformation tests as well as chemical analysis test results are presented.

4.2 Model Distribution Test and Goodness of Fit

Each of the measured properties in chapter three are now tested for goodness of fit. Test of Goodness of Fit (GOF) may be undertaken using any of the following methods: Anderson Darling test method, Chi-square test method or Kolmogorov Smirnov test method. In this study, the Kolmogorov Smirnov test method was used because of its relative advantages over Anderson Darling and Chi-square test methods which have been stated in the previous chapter. The Kolmogorov Smirnov test of goodness of fit was implemented using Easyfit statistical package.

Five distribution models were tested in this study for goodness of fit for moisture content, density, bending strength and modulus of elasticity. The distribution models are; frechet, gumbel max, lognormal, normal and Weibull. The results of these fittings are as shown below.

4.2.1 Moisture Content of Terminalia Ivorensis

The statistical parameters (mean, standard deviation and distribution model) of the moisture content for the tested test results are presented in Table 4.1. The laboratory test data for 40 *Terminalia Ivorensis* timber specimens were analysed using Easyfit statistical package.

Table 4.1: Statistical parameters of the moisture content of the Tested Terminalia Ivorensis

S/No	**Distribution**	**Parameters**
1	Frechet	α=5.106 β=15.601
2	Gumbel Max	σ=2.9952 μ=16.203
3	Lognormal	σ=0.21795 μ=2.8635
4	Normal	σ=3.8415 μ=17.932
5	Weibull	α=5.3124 β=19.224

Five commonly used distribution models for material properties were considered in the analysis, namely, Normal, lognormal, gumbel, frechet and weibull distribution models. Normal distribution is the reference model upon which all the other distribution models are based. The distribution model parameters for the Gumbel, Lognormal and Normal distribution are μ (mean) and σ (standard deviation), while the distribution model parameters for the frechet and weibull distributions are α (shape) and β (scale).

The results showed that, the tested timber specie has mean moisture content of 17.93%, standard deviation of 3.84% and the coefficient of variation of 21%. The large coefficient of variation indicate high level of uncertainty associated with moisture content of timber and it is random in nature.

Design of timber structures according to Eurocode 5 is achieved in conjunction with the EN 338 (2009) solid timber strength class, where all timber species having the same density, strength and stiffness properties are brought together under the same strength class. The EN 338 timber strength classes are based on timber reference moisture content of 12%. This implies that, the 15.52% moisture content of the Terminalia ivorensis measure in this study is higher than the 12% reference moisture content. Since as stated in the previous chapter that the material properties of timber change with change in moisture content, this implies that the values of the material properties generated in these studies will not agree with the values of strength, stiffness properties and density of timber given in EN 338. Also, as against the 12% reference moisture content for EN 338, the reference moisture content of timber of which the Nigeria code of practice (NCP 2, 1073) is 18%. The computed moisture content of the timber lies between the European and Nigeria reality. In this research, the material properties of the *Terminalia ivorensis* were adjusted to 12% and 18% reference moisture contents.

Kolmogorov Smirnov test of goodness of fit was used to determine the most suitable distribution model for the moisture content of the *Terminalia ivorensis* timber specie. This was implemented using Easyfit. The probability density functions for each of the five distribution models were plotted as shown Figures 4.1 to 4.5. These could be explained using Skewness and kurtosis.

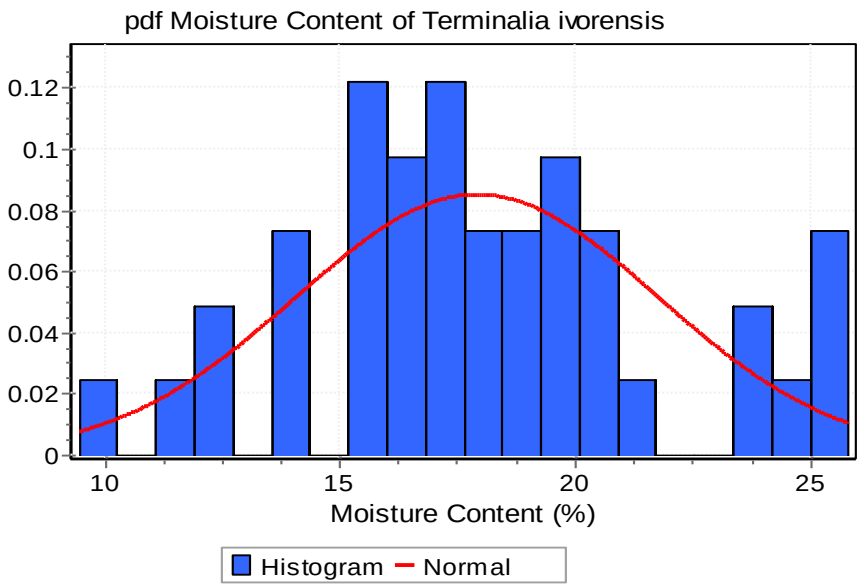

Figure 4.1: Normal distribution pdf for moisture content of *Terminalia ivorensis*

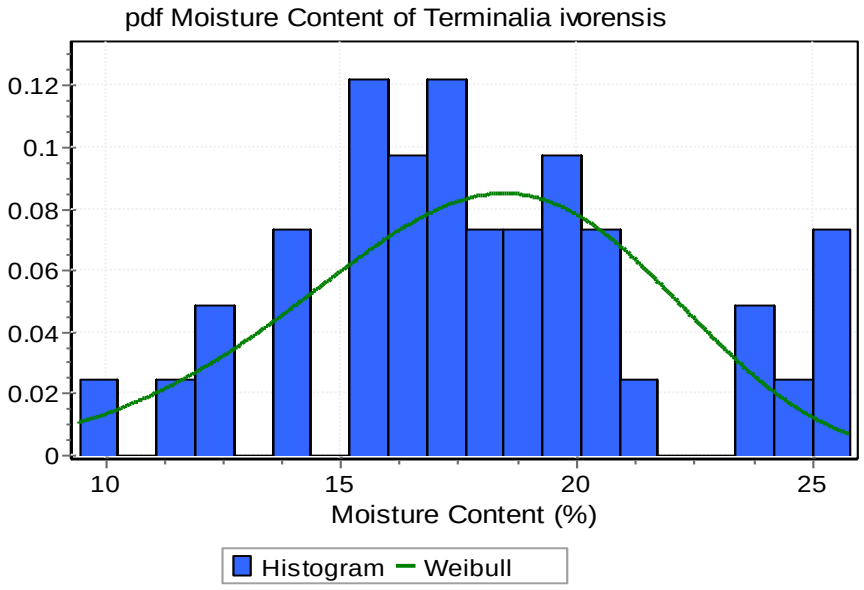

Figure 4.2: Weibull distribution pdf for moisture content of *Terminalia ivorensis*

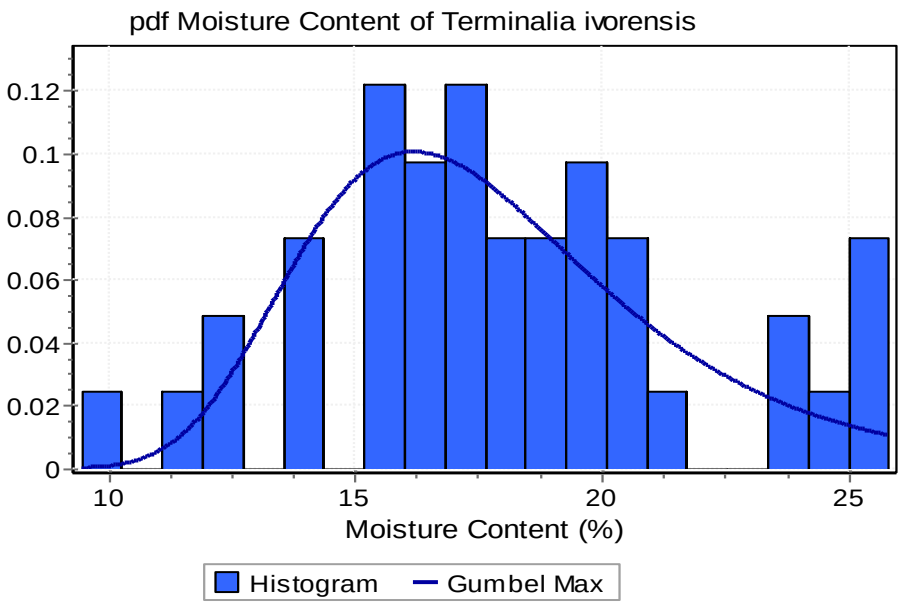

Figure 4.3: Gumbel Maximum distribution pdf for moisture content of *Terminalia ivorensis*

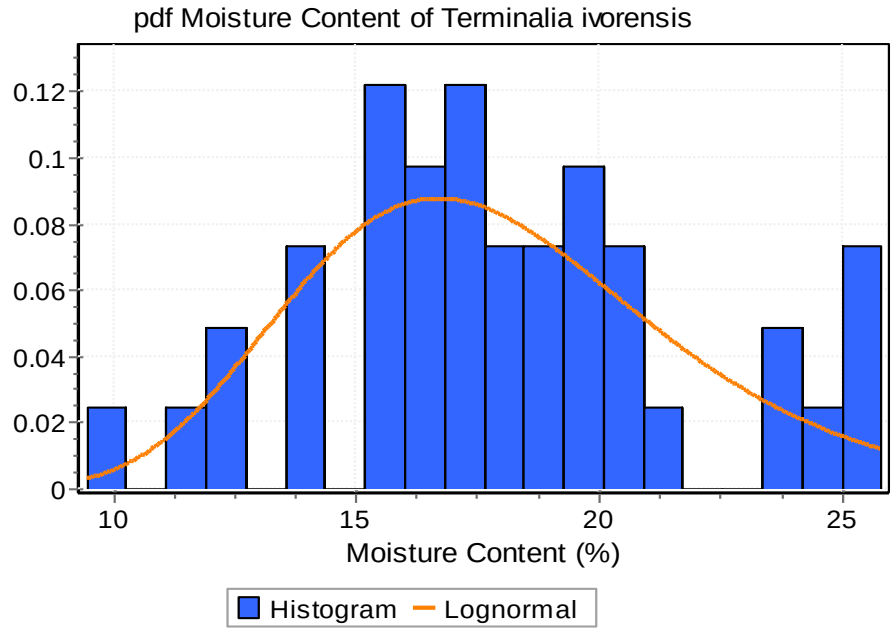

Figure 4.4: Lognormal distribution pdf for moisture content of *Terminalia ivorensis*

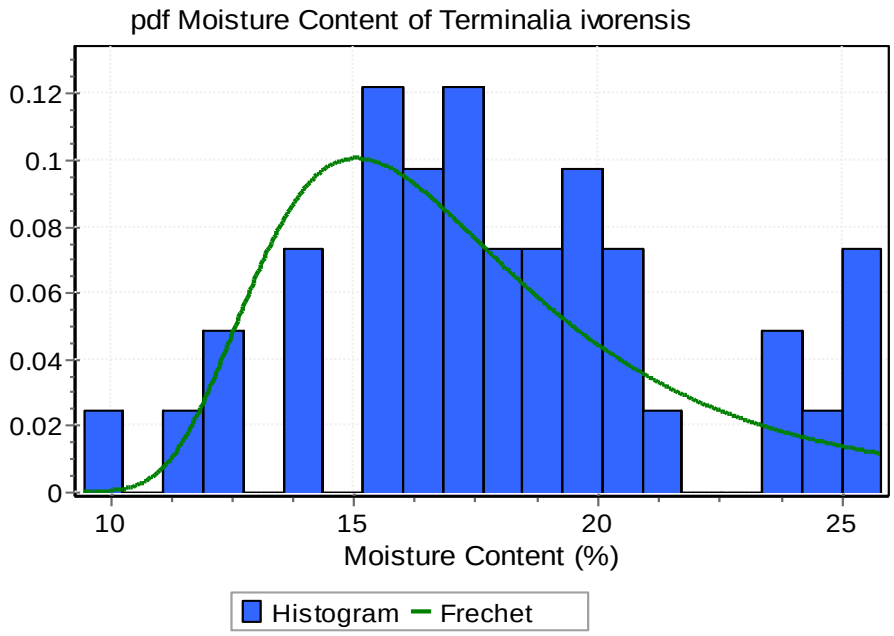

Figure 4.5: Frechet distribution pdf for moisture content of *Terminalia ivorensis*

Skewness is a measure of the asymmetry of the probability distribution of a random variable about its mean. In other words, skewness tells you the amount and direction of skew (departure from horizontal symmetry). The skewness value can be positive or negative, or even undefined. If skewness is 0, the data are perfectly symmetrical, although it is quite unlikely for real-world data. The Skewness of normally distributed variable plot is 0. As a general rule of thumb:

i. For, skewness, less than -1 or greater than 1, the distribution is highly skewed.

ii. For skewness, between -1 and -0.5 or between 0.5 and 1, the distribution is moderately skewed.

iii. For skewness, between -0.5 and 0.5, the distribution is approximately symmetric.

Kurtosis is a measure of a distribution's peak, which means how much of the distribution is centered on the distributions mean. The kurtosis of a normally distributed

data is 3. The term ‘mesokurtic is used to refer to the kurtosis of a distribution that is similar, or identical, to the kurtosis of a normally distributed data set. When a distributions kurtosis coefficient is greater than 3, the distribution is leptokurtic, and when it is less than 3, it is platykurtic.

The value of skewness and kurtosis for the fitted pdf are presented in Table 4.2. As observed from the presented results the normal distribution (Figure 4.1) has 0 skewness and 0 excess kurtosis (kurtosis equal to 3) as expected. The Weibull distribution (Figure 4.2) is negatively skewed to the left, with skewness values of -0.28 (approximately symmetric) and excess kurtosis of -0.08 (platykurtic). The gumbel maximum distribution (Figure 4.3) is positively skewed with Skewness of 1.14 (highly skewed) and excess kurtosis of 2.40 (platykurtic). The lognormal distribution (Figure 4.4) in positively skewed with coefficients of skeweness and excess kurtosis of 0.68 (moderately skewed) and 0.83 (platykurtic) respectively. The frechet distribution (Figure 4.5) is positively skewed with coefficients of skeweness and excess kurtosis of 3.45 (highly skewed) and 41.80 (Leptokurtic) respectively.

Table 4.2: Skewness and Excess Kurtosis for Moisture Content

Distribution model	Skewness	Excess Kurtosis
Normal	0	0
Weibull	-0.28	-0.08
Gumbel Maximum	1.40	2.40
Lognormal	0.68	0.83
Frechet	3.45	41.80

The Kolmogorov smirnov test of goodness of fit results for moisture content is presented in Table 4.3. The test was made at 0.2, 0.1, 0.05, 0.02 and 0.01 level ofsignificance (that

is $\alpha = 0.2, 0.1, 0.05, 0.02$ and 0.01) The hypothesis that was put forward was that, each of the five distribution models; Frechet, Gumbel maximum, Lognormal, Normal and Weibull distribution can be used to model the moisture content of *Terminalia ivorensis*. For the Frechet distribution model, the critical values for the Kolmogorov smirnov test statistics at 0.2 and 0.1 significance level were all less than the KS statistics obtained from the tests. Therefore, the hypothesis that Frechet distribution can be used to model moisture content of *Terminalia ivorensis* has to be rejected at these significant levels. However as observed from the table (Table 4.3), the critical values for KS at 0.05, 0.02 and 0.01 level of significance are all greater than the computed KS statistics. The hypothesis is now accepted that at 0.05, 0.02 and 0.01 level of significance, that Frechet distribution can be used to model moisture content of the *Terminalia ivorensis* timber. It is also clear from the table, that the critical values of the KS at all the considered level of significance are all greater than the KS statistics for the Gumbel maximum, Lognormal, Normal and the Weibull distributions. Therefore, all these distributions can be considered as acceptable distribution models for moisture content of *Terminalia ivorensis*. However, looking at the KS statistics for all the five distributions, Normal distribution has the least KS statistics, followed by Weibull distribution, Gumbel maximum distribution, Lognormal distribution and the Frechet distribution in increasing order of KS statistics. The distribution models were ranked with the distribution model having the least KS statistics being considered as rank 1.

Therefore, based on the results obtained and presented, the normal distribution is the best model for the moisture content of *Terminalia ivorensis*.

Table 4.3: Results of Kolmogorov Smirnov Test of Goodness of fit for Moisture Content

S/No	Distribution model	α=0.2	α=0.1	α=0.05	α=0.02	α=0.01	KS Statistics	Rank
		0.1655	0.1891	0.2101	0.2349	0.2521		
1	Frechet	Yes	Yes	No	No	No	0.1904	5
2	Gumbel Maximum	No	No	No	No	No	0.1176	3
3	Lognormal	No	No	No	No	No	0.1198	4
4	Normal	No	No	No	No	No	0.0994	1
5	Weibull	No	No	No	No	No	0.1051	2

4.2.2 Density of Terminalia Ivorensis

The statistical parameters (mean, standard deviation and distribution model) of the density for the tested *Terminalia ivorensis* timber are presented in Table 4.4. The laboratory test data for 40 *Terminalia Ivorensis* timber specimens were analysed using Easyfit statistical package.

Again, five commonly used distribution models for material properties were considered in the analysis, namely, Normal, lognormal, gumbel, frechet and weibull distribution models. Normal distribution is the reference model upon which all the other distribution models are based. The distribution model parameters for the Gumbel, Lognormal and Normal distribution are μ (mean) and σ (standard deviation), while the distribution model parameters for the frechet and weibull distributions are α (shape) and β (scale).

The results showed that, the tested timber specie has mean density of 449.24kg/m^2 and standard deviation of 68.105kg/m^3. This is equivalent to 15.2% coefficient of variation.

Table 4.4: Statistical parameters of the density of the Tested *Terminalia Ivorensis*

S/No	**Distribution**	**Parameters**
1	Frechet	α=7.4395 β=409.57
2	Gumbel Max	σ=53.101 μ=418.59
3	Lognormal	σ=0.15237 μ=6.0961
4	Normal	σ=68.105 μ=449.24
5	Weibull	α=7.7767 β=472.53

The results of Kolmogorov smirnov test for the density of *Terminalia ivorensis* timber is presented in this section. Similarly, as for the moisture contents, the density test data was fitted to five distribution models; normal, lognormal, Weibull, gumbel and frechet. The probability density function plots are plotted in Figures 4.6 to 4.10.

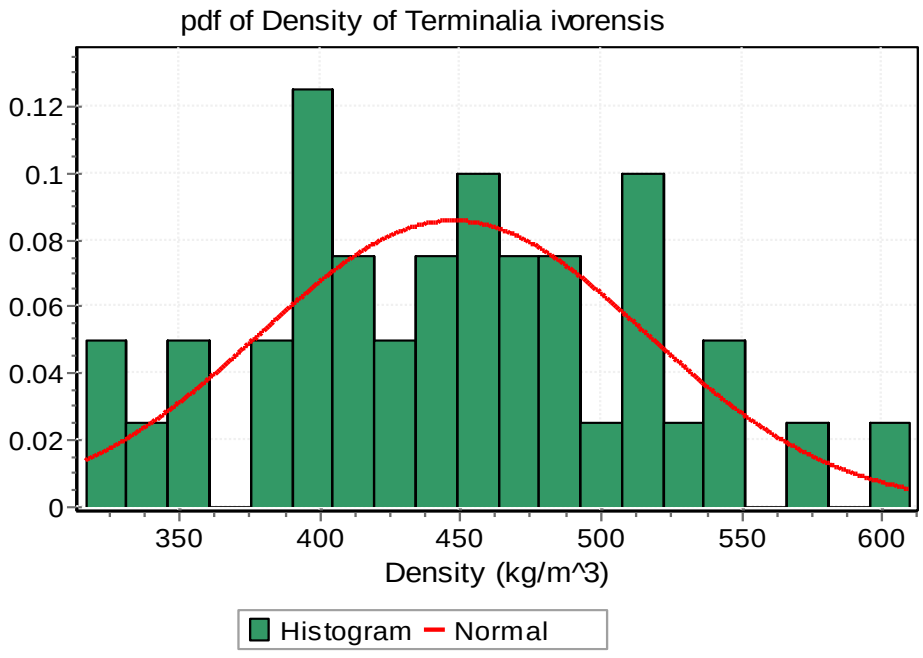

Figure 4.6: Normal distribution pdf for Density of *Terminalia ivorensis*

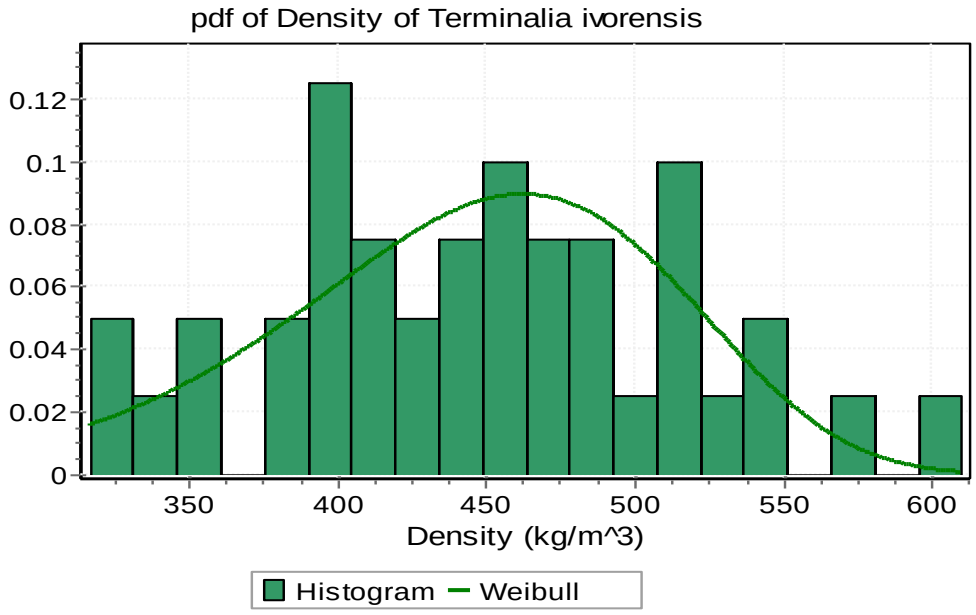

Figure 4.7: Weibull distribution pdf for Density of *Terminalia ivorensis*

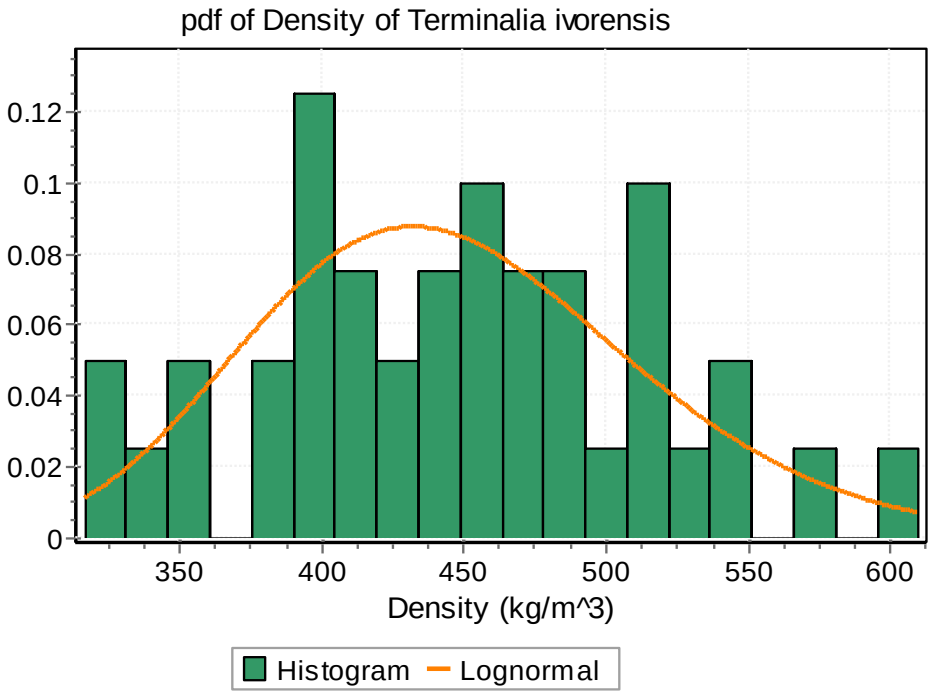

Figure 4.8: Lognormal distribution pdf for Density of *Terminalia ivorensis*

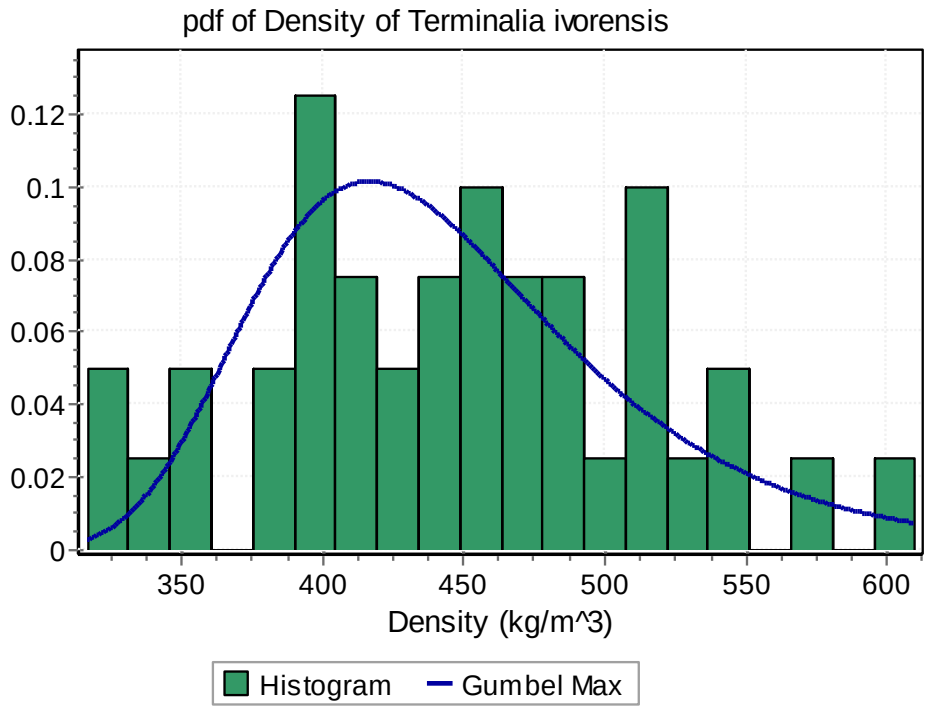

Figure 4.9: Gumbel Maximum distribution pdf for Density of *Terminalia ivorensis*

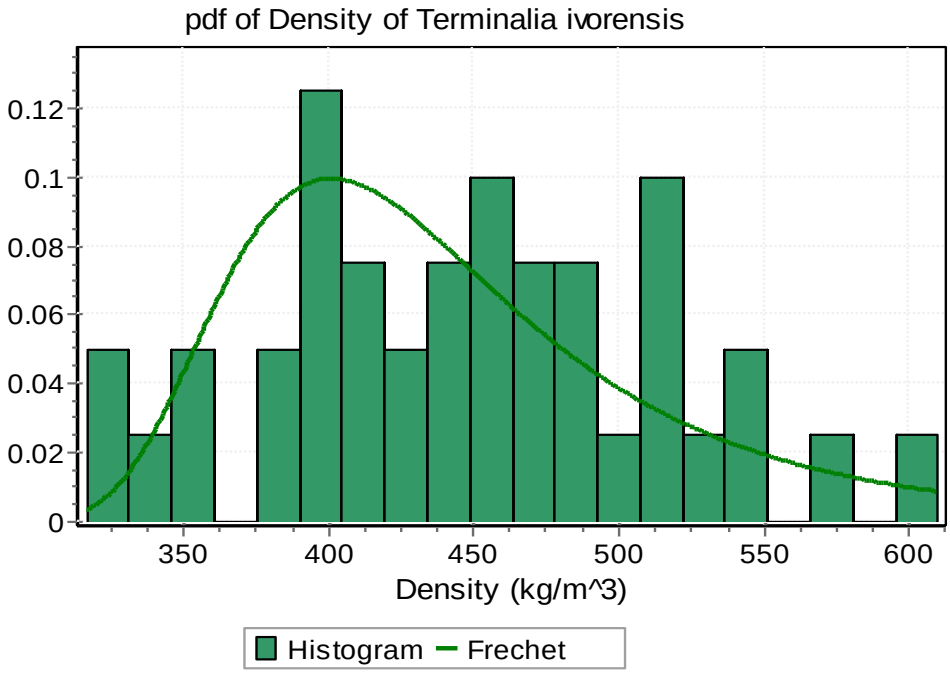

Figure 4.10: Frechet distribution pdf for Density of Terminalia ivorensis

The coefficients of skewness and excess kurtosis are presented in Table 4.5. As observed from the presented results the normal distribution (Figure 4.6) has 0 skewness and 0 excess kurtosis (kurtosis equal to 3) as expected. The Weibull distribution (Figure 4.7) is negatively skewed to the left, with skewness values of -0.517 (moderately skewed) and excess kurtosis of 0.293 (platykurtic). The lognormal distribution (Figure 4.8) is positively skewed with Skewness of 0.485 (approximately symmetric) and excess kurtosis of 0.387 (platykurtic). The gumbel maximum distribution (Figure 4.9) in positively skewed with coefficients of skewness and excess kurtosis of 1.140 (highly skewed) and 2.40 (platykurtic) respectively. The frechet distribution (Figure 4.10) is positively skewed with coefficients of skewness and excess kurtosis of 2.318 (highly skewed) and 12.77 (Leptokurtic) respectively.

Table 4.5: Skewness and Excess Kurtosis for Density

Distribution model	Skewness	Excess Kurtosis
Normal	0	0
Weibull	-0.52	0.30
Gumbel Maximum	1.14	2.40
Lognormal	0.49	0.39
Frechet	2.32	12.77

The Kolmogorov smirnov test of goodness of fit results for density of the Terminalia ivorensis is presented in Table 4.6. The test was made at 0.2, 0.1, 0.05, 0.02 and 0.01 (that is $\alpha = 0.2, 0.1, 0.05, 0.02$ and 0.01)level of significance based on the hypothesis that, each of the five distribution models; Frechet, Gumbel maximum, Lognormal, Normal and Weibull distribution can be used to model the moisture content of *Terminalia ivorensis*.

As observed from the table (Table 4.6), the critical values of the KS at all the considered level of significance are all greater than the KS statistics for all the distribution models (Frechet, Gumbel maximum, Lognormal, Normal and the Weibull distributions) considered in this study. Therefore, all the distribution can be considered as acceptable distribution models for density of *Terminalia ivorensis*.

However, looking at the KS statistics for all the five distributions, Normal distribution has the least KS statistics, followed by Weibull distribution, Lognormal, Gumbel maximum distribution, and then Frechet distribution in increasing order of KS statistics. The distribution models were ranked with the distribution model having the least KS statistics being considered as rank 1. Therefore, based on the results obtained and presented, the normal distribution is also the best model for the density of *Terminalia ivorensis.*

Table 4.6: Results of Kolmogorov Smirnov Test of Goodness of fit for Density

S/No	Distribution model	α=0.2	α=0.1	α=0.05	α=0.02	α=0.01	KS Statistics	Rank
		0.1655	0.1891	0.2101	0.2349	0.2521		
1	Frechet	No	No	No	No	No	0.152	5
2	Gumbel Maximum	No	No	No	No	No	0.104	4
3	Lognormal	No	No	No	No	No	0.070	3
4	Normal	No	No	No	No	No	0.055	1
5	Weibull	No	No	No	No	No	0.064	2

4.2.3 Bending Strength of Terminalia Ivorensis

The statistical parameters (mean, standard deviation and distribution model) of the bending strength of the tested *Terminalia ivorensis* timber are presented in Table 4.7. The laboratory test data for 40 *Terminalia Ivorensis* timber specimens were analysed using Easyfit statistical package. The commonly used distribution models considered in the analysis, are Normal, lognormal, gumbel, frechet and weibull distribution models. The results showed that, the tested timber specie has mean bending strength of 109.49N/mm^2 and standard deviation of 17.62N/mm^2. This is equivalent to 16.09% coefficient of variation.

Table 4.7: Statistical parameters of the bending strength of the Tested *Terminalia Ivorensis*

S/No	**Distribution**	**Parameters**
1	Frechet	α=6.643 β=98.865
2	Gumbel Max	σ=13.739 μ=101.56
3	Lognormal	σ=0.16479 μ=4.6826
4	Normal	σ=17.621 μ=109.49
5	Weibull	α=7.033 β=115.9

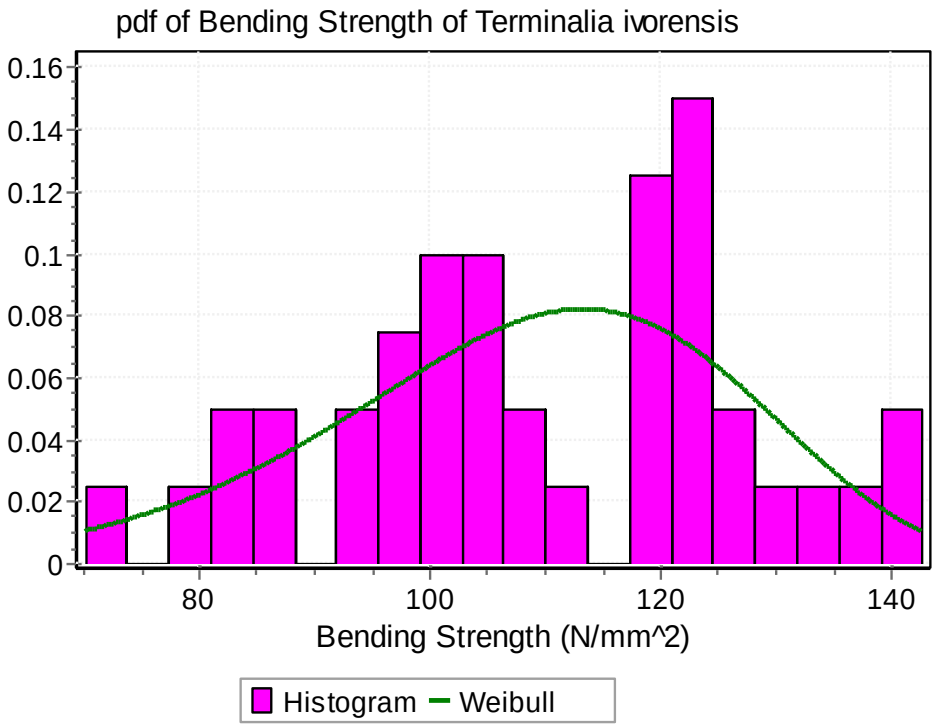

Figure 4.11: Weibull distribution pdf for bending strength of *Terminalia ivorensis*

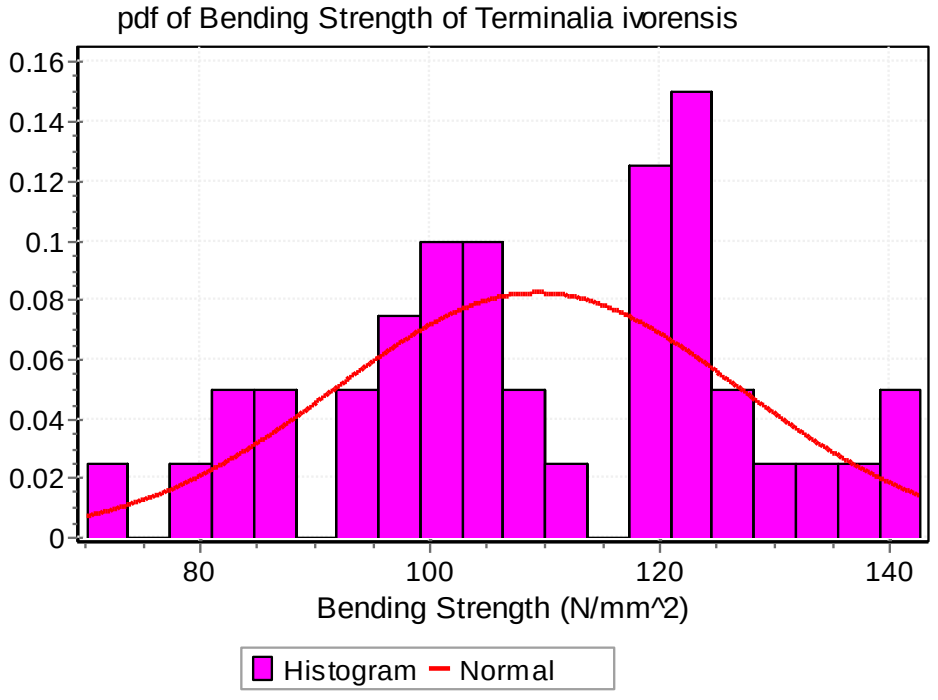

Figure 4.12: Normal distribution pdf for bending strength of *Terminalia ivorensis*

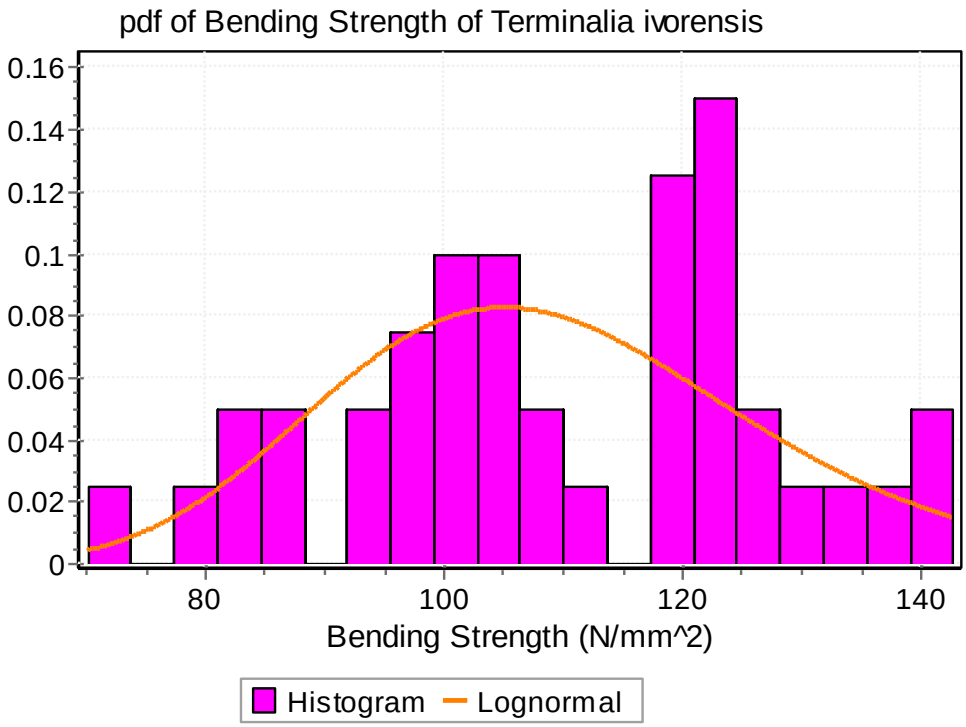

Figure 4.13: Lognormal distribution pdf for bending strength of *Terminalia ivorensis*

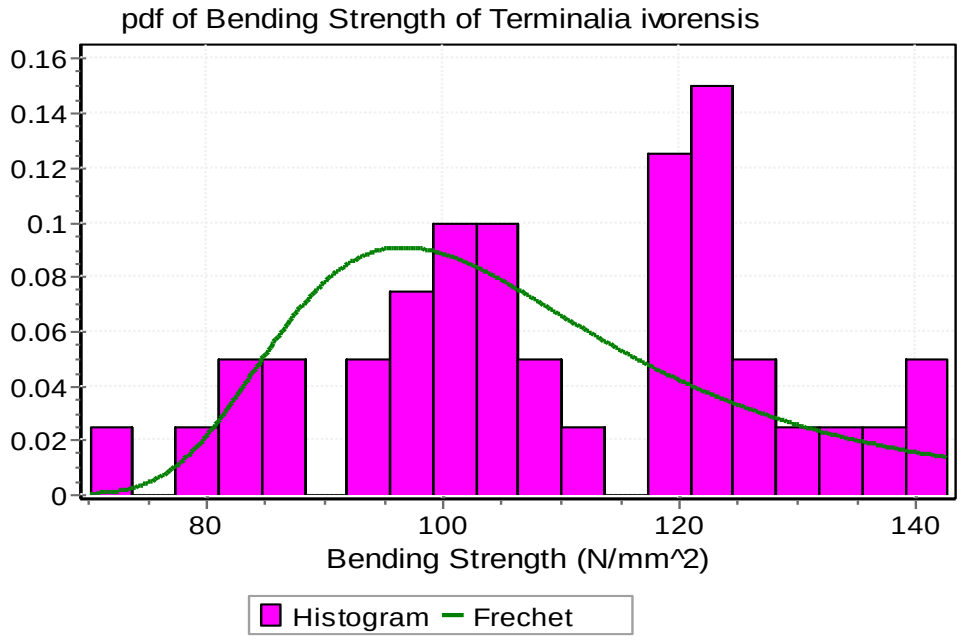

Figure 4.14: Frechet distribution pdf for bending strength of *Terminalia ivorensis*

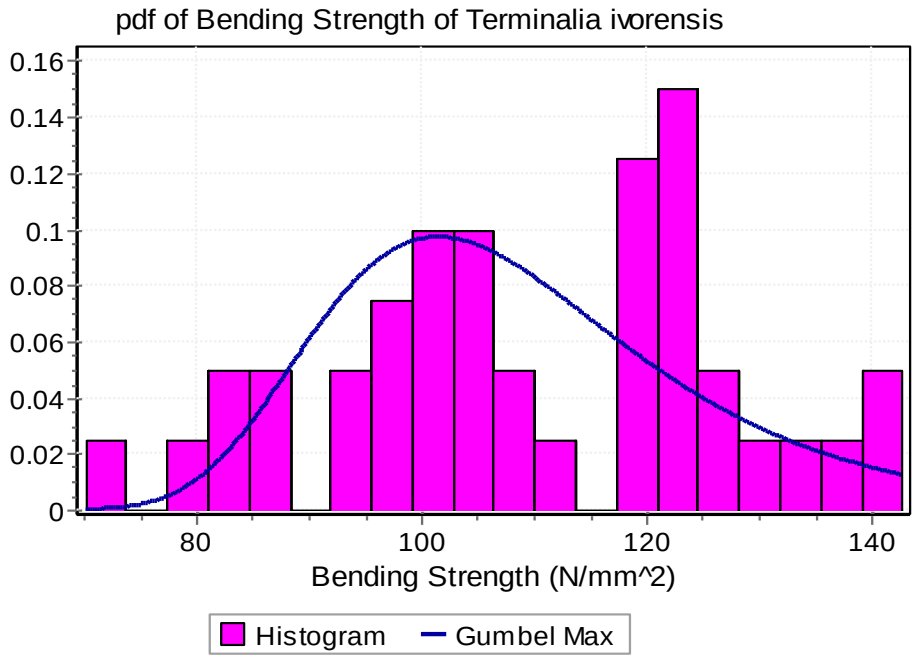

Figure 4.15: Gumbel maximum distribution pdf for bending strength of *Terminalia ivorensis*

The values of skewness and excess kurtosis are presented in Table 4.8. As observed from the presented results, the Weibull distribution (Figure 4.11) is negatively skewed to the left, with skewness values of -0.866 (moderately skewed) and excess kurtosis of 0.293 (platykurtic). The normal distribution (Figure 4.12) has 0 skewness and 0 excess kurtosis (kurtosis equal to 3) as expected). The lognormal distribution (Figure 4.13) is positively skewed with coefficients of skewness and excess kurtosis of 0.502 (moderately skewed) and 0.451 (platykurtic) respectively. The frechet distribution (Figure 4.14) is positively skewed with coefficients of skewness and excess kurtosis of 2.53 (highly skewed) and 16.42 (Leptokurtic) respectively. The gumbel maximum distribution (Figure 4.15) is also positively skewed with Skewness of 1.14 (highly skewed) and excess kurtosis of 2.40 (platykurtic).

Table 4.8: Skewness and Excess Kurtosis for bending strength

Distribution model	Skewness	Excess Kurtosis
Normal	0	0
Weibull	-0.866	0.192
Gumbel Maximum	1.14	2.40
Lognormal	0.502	0.451
Frechet	2.53	16.42

The Kolmogorov smirnov test of goodness of fit results for bending strength of the *Terminalia ivorensis* is presented in Table 4.9. The test was made at 2%, 1%, 0.5%, 0.2% and 0.1% level of significance based on the hypothesis that, each of the five distribution models; Frechet, Gumbel maximum, Lognormal, Normal and Weibull distribution can be used to model the moisture content of *Terminalia ivorensis*. As observed from the table (Table 4.9), the critical values of the KS at all the considered level of significance are all greater than the KS statistics for all the distribution models (Frechet, Gumbel maximum, Lognormal, Normal and the Weibull distributions) considered in this study.

Therefore, all the distribution can be considered as acceptable distribution models for bending strength of *Terminalia ivorensis*. However, looking at the KS statistics for all the five distributions, Weibull distribution has the least KS statistics, followed by Normal distribution, Lognormal, Gumbel maximum distribution, and then Frechet distribution in increasing order of KS statistics. The distribution models were ranked with the distribution model having the least KS statistics being considered as rank 1. Therefore, based on the results obtained and presented, the Weibull distribution is also the best model for the bending strength of *Terminalia ivorensis.*

Table 4.9: Results of Kolmogorov Smirnov Test of Goodness of fit for bending strength

S/No	Distribution model	α=0.2	α=0.1	α=0.05	α=0.02	α=0.01	KS Statistics	Rank
		0.1655	0.1891	0.2101	0.2349	0.2521		
1	Frechet	No	No	No	No	No	0.179	5
2	Gumbel Maximum	No	No	No	No	No	0.182	4
3	Lognormal	No	No	No	No	No	0.146	3
4	Normal	No	No	No	No	No	0.127	2
5	Weibull	No	No	No	No	No	0.119	1

4.2.4 Modulus of Elasticity of Terminalia Ivorensis

The statistical parameters (mean, standard deviation and distribution model) of the bending modulus of elasticity of the tested *Terminalia ivorensis* timber are presented in Table 4.10.

Table 4.10: Statistical parameters of the modulus of elasticity of the Tested *Terminalia Ivorensis*

S/No	**Distribution**	**Parameters**
1	Frechet	α=4.8607 β=13985.0
2	Gumbel Max	σ=2708.1 μ=14608.0
3	Lognormal	σ=0.22364 μ=9.667
4	Normal	σ=3473.3 μ=16171.0
5	Weibull	α=5.1556 β=17374.0

The laboratory test data for 40 *Terminalia Ivorensis* timber specimens were analysed using Easyfit statistical package. The commonly used distribution models considered in the analysis are Normal, lognormal, gumbel, frechet and weibull distribution models. The results shown that, the tested timber specie has mean modulus of

elasticity of 16171N/mm^2 and standard deviation of 3473.3N/mm^2. This is equivalent to 21% coefficient of variation.

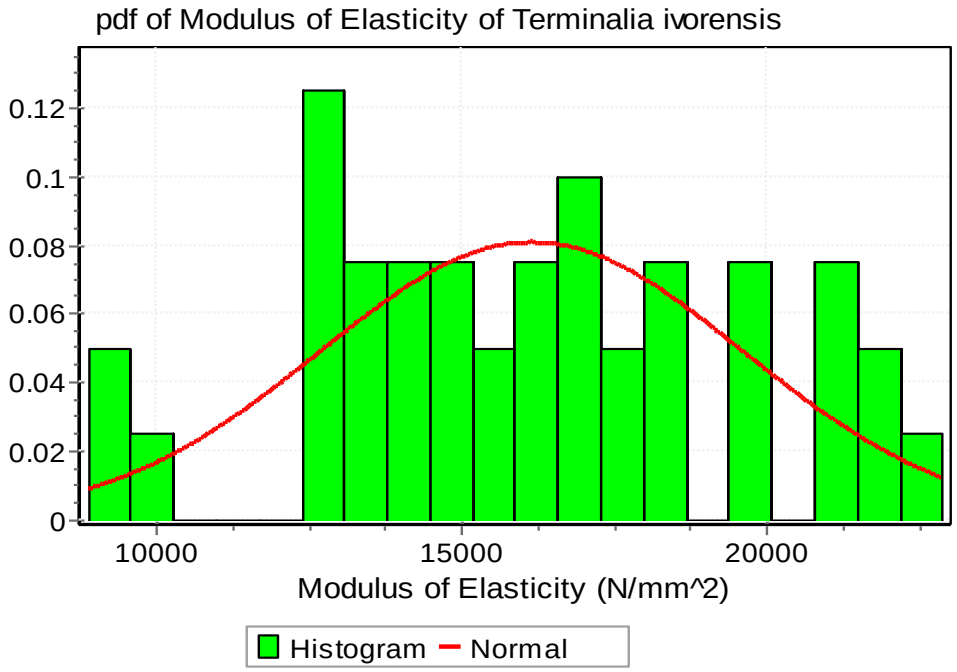

Figure 4.16: Normal distribution pdf for modulus of elasticity of *Terminalia ivorensis*

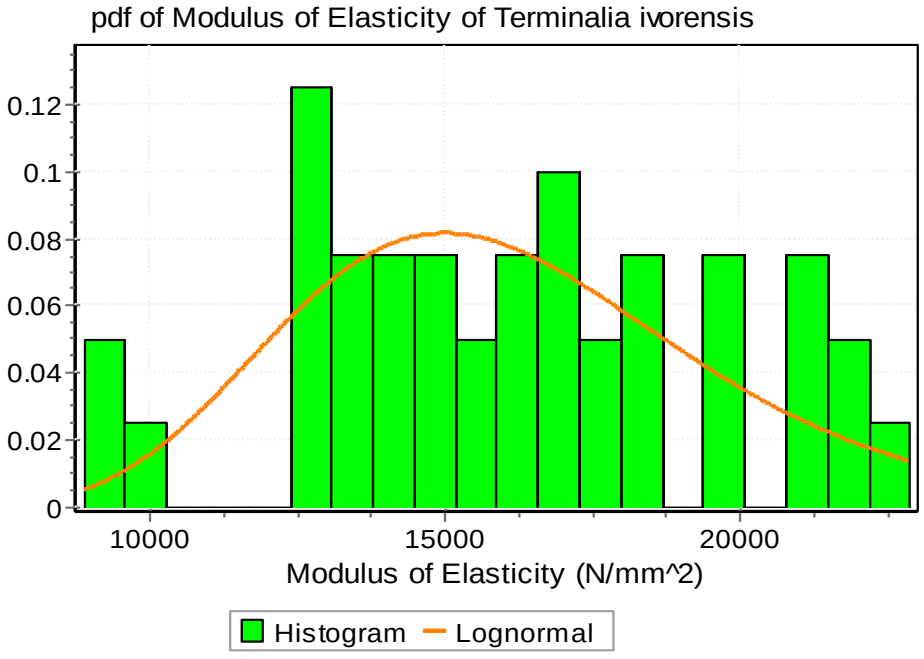

Figure 4.17: Lognormal distribution pdf for modulus of elasticity of *Terminalia ivorensis*

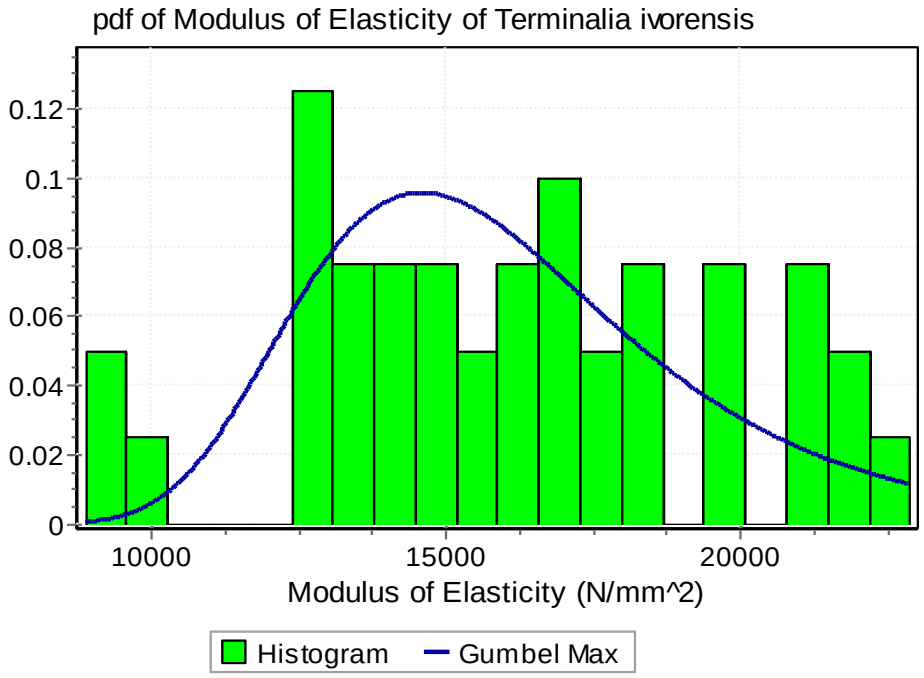

Figure 4.18: Gumbel Maximum distribution pdf for modulus of elasticity of *Terminalia ivorensis*

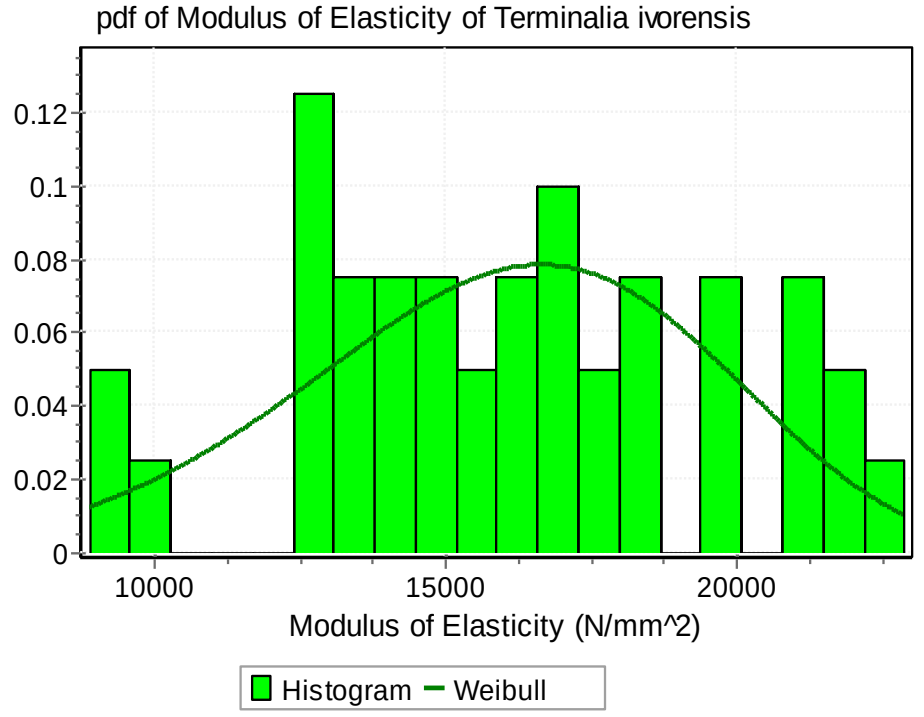

Figure 4.19: Weibull distribution pdf for modulus of elasticity of *Terminalia ivorensis*

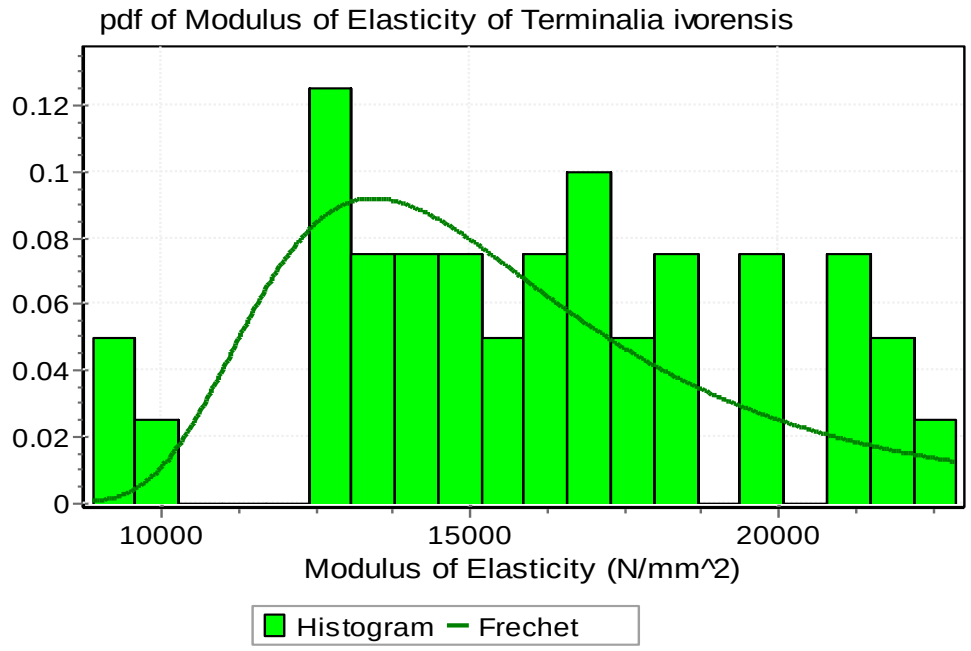

Figure 4.20: Frechet distribution pdf for modulus of elasticity of *Terminalia ivorensis*

The values of skewness and excess kurtosis are presented in Table 4.11. As observed from the presented results, the normal distribution (Figure 4.16) has 0 skewness and 0 excess kurtosis (kurtosis equal to 3) as expected. The Lognormal distribution (Figure 4.17) is positively skewed with Skewness of -0.691 (moderately skewed) and excess kurtosis of 0.861 (platykurtic). The gumbel maximum distribution (Figure 4.18) is positively skewed with coefficients of skewness and excess kurtosis of 1.140 (highly skewed) and 2.40 (platykurtic) respectively. The Weibull distribution (Figure 4.19) is negatively skewed to the left, with skewness values of -0.275 (approximately symmetric) and excess kurtosis of -0.096 (platykurtic). The Frechet distribution (Figure 4.20) is positively skewed with coefficients of skewness and excesskurtosis of 3.695 (highly skewed) and 53.053 (Leptokurtic) respectively.

Table 4.11: Skewness and Excess Kurtosis for modulus of elasticity

Distribution model	Skewness	Excess Kurtosis
Normal	0	0
Weibull	-0.275	-0.096
Gumbel Maximum	1.14	2.40
Lognormal	0.691	0.861
Frechet	3.695	53.053

The Kolmogorov smirnov test of goodness of fit results for modulus of elasticity of the Terminalia ivorensis is presented in Table 4.12. The test was made at 2%, 1%, 0.5%, 0.2% and 0.1% level of significance based on the hypothesis that, each of the five distribution models; Frechet, Gumbel maximum, Lognormal, Normal and Weibull distribution can be used to model the modulus of elasticity of Terminalia ivorensis. As observed from the table (Table 4.12), the critical values of the KS at all the considered level of significance are all greater than the KS statistics for all the distribution models (Frechet, Gumbel maximum, Lognormal, Normal and the Weibull distributions) considered in this study. Therefore, all the distribution can be considered as acceptable distribution models for modulus of elasticity of Terminalia ivorensis.

However, looking at the Kolmogorov Smirnov (KS) statistics for all the five distributions, lognormal distribution has the least KS statistics, followed by Normal distribution, Gumbel maximum, Weibull distribution, and then Frechet distribution in increasing order of KS statistics. The distribution models were ranked with the distribution model having the least KS statistics being considered as rank 1. Therefore, based on the results obtained and presented, the Lognormal distribution is also the best model for the modulus of elasticity of Terminalia ivorensis.

Table 4.12: Results of Kolmogorov Smirnov Test of Goodness of fit for modulus of elasticity

S/No	Distribution model	α=0.2	α=0.1	α=0.05	α=0.02	α=0.01	KS Statistics	Rank
		0.1655	0.1891	0.2101	0.2349	0.2521		
1	Frechet	No	No	No	No	No	0.1351	5
2	Gumbel Maximum	No	No	No	No	No	0.0877	3
3	Lognormal	No	No	No	No	No	0.0077	1
4	Normal	No	No	No	No	No	0.0747	2
5	Weibull	No	No	No	No	No	0.0890	4

4.3 Stochastic Models of Material Properties

The Eurocodes 0 (2004) and Eurocode 5 (2004) design criteria of solid timber is semi-probabilistic in nature. This is based on the fact that, the code recognized that, the material properties of structural timber are uncertain, tried to accommodate the uncertainties by the use of conservative safety factors.

For example, the Eurocode 0 (2004) clearly stated that, the partial safety factors for structural design could be determined in either of two ways; The partial safety factors could be established from long term experience of building tradition (deterministic/semi-probabilistic), it could be established using reliability based calibration by experimental data.

The code went further to state that, the first method was used to come up with the current safety factors in the Eurocode but to accommodate the uncertainties associated with the basic design variables, the second method is the best.

To perform reliability based structural design considering either ultimate or serviceability limit states, there is the need to generate the stochastic models (mean, standard deviation, coefficient of variation and distribution models) for the material properties.

The summary of the various distributions for the stochastic model of the reference properties of Terminalia ivorensis; moisture content, density, bending strength and material properties based on the results obtained in this study, are calculated and presented in Table 4.13 below.

Table 4.13: Stochastic models of the material properties of the *Terminalia ivorensis*

Material Properties	Mean	Standard deviation	Coefficient of variation	Distribution models
Moisture content (%)	17.93	3.84	0.22	Normal
Density (kg/m^3)	449.24	68.40	0.15	Normal
Bending strength (N/mm^2)	109.49	17.62	0.16	Weibull
Modulus of elasticity (N/mm^2)	16171.0	3473.3	0.21	Lognormal

4.4 Moisture Adjusted Material Properties

Properties of timber vary with variation in moisture content below and above the fibre saturation point (Ranta-Maunus, 2001). The EN 384 (2004) is based upon the reference moisture content of 12% while that of NCP2 (1973) is based on 18%.

The moisture content of the *Terminalia ivorensis* obtained during the test is 17.86%. To classify the *Terminalia ivorensis* based on the EN 338 strength classes, the reference material properties (density, bending strength and modulus of elasticity) have to be adjusted to the 12% reference moisture content. The 12% moisture content adjusted material properties are presented in Table 4.14.

Also, to enable the use of the results presented in this study for the timber strength classes of timber that is based on Nigerian 18% reference moisture content (which is a hope for the near future), the material properties in this study were also adjusted to 18% reference moisture content, using linear interpolation, considering the values obtained using the measured moisture content and the 12% reference moisture content.

Using the average values of reference material properties obtained in the study, the 12% and 18% are calculated from equations 2.19 to 2.21as earlier discussed in pages 53 and 54 of chapter two.

Table 4.14: Moisture Adjusted Reference Material Properties

Moisture Content (%)		Density (kN/m^3)	Bending Strength (N/mm^2)	Modulus of Elasticity (N/mm^2)
Test Moisture Content	17.93	449.24	109.49	16171.0
EN 384, (2004), Reference moisture content	12	434.75	69.10	13181.5
NCP 2, 1973, Reference moisture content	18	448.19	81.33	16242.79

4.4.1 Adjustment Factors for Bending Strength

EN 408 (2004) required that, the test piece shall be systematically loaded in bending over a span 18 times its depth as shown in Figure 3.1. The reference depth is 150mm. For test pieces that do not meet the EN 408 (2004) dimension specification, EN 384 (2004) recommended adjustment factors for bending and tensile strengths only (Clause 5.3.4.3). According to EN 384 (2004), the bending and tensile strength shall be adjusted to 150mm reference depth by dividing by an adjustment factor k_h obtained using equation 4.1.

$$k_h = \left(\frac{150}{h}\right)^{0.2} \tag{4.1}$$

Where, h = the actual depth of the test piece in mm.

Also, for length other than that specified in the EN 408 (2004), the bending strength be adjusted by with an adjustment factor K_1 obtained using equation 4.2.

$$K_1 = \left(\frac{L_{es}}{L_{et}}\right)^{0.2} \tag{4.2}$$

Where L_{es} = specimen used in the experiment and

L_{et}= the standard length of the specimen.

L_{es} and L_{et} are calculated using equations 4.3 and 4.4 respectively as follows:

$$L_{es} = L_{asp} + 5a_{fasp} \quad (4.3)$$

Where L_{asp} = the actual length of specimen used in the experiment,

a_{fsp}= distance between the point loads for the actual specimen.

$$L_{et} = L_{std} + 5a_{fstd} \quad (4.4)$$

Where L_{std} is the length of standard length of the specimen, which is 18 times the standard depth of 150mm, where

a_{fstd}= distance between the point loads for the standard specimen.

The bending strength adjustment factor for depth is determined using equation 4.1 as follows:

$$k_h = \left(\frac{150}{75}\right)^{0.2} = 1.1485$$

The bending strength adjustment factor for length is determined using equation 4.2 as follows:

$$\left(\frac{2700+(5x600)}{1200+(5x400)}\right)^{0.2} = 1.122$$

Therefore, the adjusted bending strength is given by:

$$m = 1.12x1.15x60.3 = 77.7\text{N/mm}^2$$

Table 4.15: Bending Strength Adjustment to Standard Depth and Length

S/No	Sample No	Bending Strength (N/mm^2)	Length Adjustment Factor, k_1	Depth adjustment, k_h	Adjusted Bending Strength (N/mm^2)
1	D-1	60.3	1.12	1.15	77.7
2	D-2	78.4	1.12	1.15	105.9
3	D-3	71.6	1.12	1.15	96.7
4	D-4	59.7	1.12	1.15	80.7
5	D-5	75.3	1.12	1.15	101.7
6	D-6	102.8	1.12	1.15	138.8
7	D-7	87.6	1.12	1.15	118.3
8	D-8	81.3	1.12	1.15	109.9
9	D-9	78.9	1.12	1.15	106.6
10	D-10	92.5	1.12	1.15	125.0
11	D-11	87.0	1.12	1.15	117.6
12	D-12	88.6	1.12	1.15	119.7
13	D-13	63.5	1.12	1.15	85.8
14	D-14	70.1	1.12	1.15	94.8
15	D-15	104.9	1.12	1.15	141.7
16	D-16	97.7	1.12	1.15	132.0
17	D-17	74.7	1.12	1.15	100.9
18	D-18	89.9	1.12	1.15	121.5
19	D-19	87.0	1.12	1.15	117.6
20	D-20	105.7	1.12	1.15	142.7
21	D-21	82.1	1.12	1.15	105.7
22	D-22	90.4	1.12	1.15	122.1
23	D-23	60.8	1.12	1.15	82.1
24	D-24	71.1	1.12	1.15	96.1

Table 4.15: Bending Strength Adjustment to Standard Depth and Length (Contd.)

S/No	Sample No	Bending Strength (N/mm^2)	Length Adjustment Factor, k_1	Depth adjustment, k_h	Adjusted Bending Strength (N/mm^2)
25	D-25	75.3	1.12	1.15	101.7
26	D-26	76.2	1.12	1.15	103.0
27	D-27	92.0	1.12	1.15	124.2
28	D-28	64.7	1.12	1.15	87.5
29	D-29	77.5	1.12	1.15	104.7
30	D-30	52.0	1.12	1.15	70.2
31	D-31	69.5	1.12	1.15	93.9
32	D-32	76.9	1.12	1.15	103.9
33	D-33	90.5	1.12	1.15	122.2
34	D-34	97.2	1.12	1.15	131.3
35	D-35	90.4	1.12	1.15	122.1
36	D-36	72.7	1.12	1.15	98.3
37	D-37	75.2	1.12	1.15	101.6
38	D-38	87.1	1.12	1.15	117.7
39	D-39	89.6	1.12	1.15	121.0
40	D-40	93.1	1.12	1.15	125.8

The adjusted bending strength was determined for each test piece, and the results are presented in table 4.15 above.

4.5 Other Material Properties

The modulus of elasticity, bending strength and density obtained from the laboratory are known as the reference properties of timber. Other strength and stiffness properties are calculated from the reference properties in accordance with the recommendation of EN 384 (2004) and JCSS (Joint Committee of Structural safety) Probilistic Model Code (2006). The other material properties include:

a) $f_{t,0}$ (Tension Strength parallel to grain)

b) $f_{t,90}$ (Tension Strength perpendicular to grain)

c) $E_{t,0}$ (Tension Modulus of Elasticity parallel to grain)

d) $E_{t,90}$ (Tension Modulus of Elasticity perpendicular to grain)

e) $f_{c,0}$ (Compression strength parallel to grain)

f) $f_{c,90}$ (Compression strength perpendicular to grain)

g) $E_{c,0}$ (Compression Modulus of Elasticity parallel to grain)

h) $E_{c,90}$ (Compression Modulus of Elasticity perpendicular to grain)

i) f_v (Shear Strength)

j) G_v (Shear Modulus)

k) $f_{h,0}$ (Embedding Strength parallel to grain)

l) $f_{h,90}$(Embedding Strength perpendicular to grain.

The relationships between the reference properties of timber (bending strength, bending modulus of elasticity and density) and other timber properties (tension parallel and perpendicular to grain, compression parallel and perpendicular to grain etc) were determined using 4.5 to 4.12 according to EN 384 (2004) and JCSS (2006):

$$f_{t,0} = 0.6R_m \quad (4.5)$$

$$f_{t,90} = 0.015\rho_{den} \quad (4.6)$$

$$E_{t,0} = R_m \quad (4.7)$$

$$E_{t,90} = E_m/90 \quad (4.8)$$

$$f_{c,0} = 5(R_m)^{0.45} \quad (4.9)$$

$$f_{c,90} = 0.08\rho_{den} \quad (4.10)$$

$$G_v = E_m/16 \quad (4.11)$$

$$f_v = 0.2(R_m)^{0.8} \quad (4.12)$$

Where, R_m is the bending strength parallel to the grain,

E_m is the modulus of elasticity

ρ_{den} the density.

R_m, E_m and ρ_{den} are the reference material properties measured from the laboratory test data.

$f_{t,0}$ is the tension strength parallel to grain,

$f_{t,90}$ is the tension strength perpendicular to grain, $E_{t,0}$ is the tension elastic modulus, parallel to grain,

$E_{t,90}$is the tension elastic modulus perpendicular to grain,

$f_{c,0}$ is the compression strength parallel to grain,

$f_{c,90}$is the compression strength perpendicular to grain,

G_v is the shear modulus, f_v is the shear strength.

The derived tension strength parallel to grain, $f_{t,0}$, tension strength perpendicular to grain, $f_{t,90}$, compression strength parallel to grain, $f_{c,0,}$ compression strength perpendicular to grain $f_{c,90}$ and the shear strength, f_v, considering the first specimen (E-1) are determined respectively using equations 4.5, 4.6, 4.9, 4.10 and 4.12 as follows:

$f_{t,0} = 0.6x77.7 = 46.62\text{N/mm}^2$

$f_{t,90} = 0.015x502.3 = 7.6\text{N/mm}^2$

$f_{t,90} = 5x77.7^{0.45} = 35.45\text{N/mm}^2$

$f_{c,90} = 0.08x502.3 = 40.18\text{N/mm}^2$

$f_{v} = 0.2x(77.7)^{0.8} = 6.51\text{N/mm}^2$

The derived strength properties were determined for each of the forty members and the results are presented in table 4.16

Similarly, the derived tension elastic modulus, parallel to grain, $E_{t,0}$, tension elastic modulus, perpendicular to grain $E_{t,90}$, and shear modulus, G_v considering the first specimen are determined respectively using equations 4.7, 4.8 and 4.11 as follows:

$E_{t,0} = R_m = 77.7\text{ N/mm}^2$

$E_{t,90} = \frac{15955.23}{90} = 177.3\text{N/mm}^2$

$G_v = \frac{15955.23}{16} = 997.20\text{N/mm}^2$

Also, derived stiffness properties for Terminalia ivorensis for each of the forty memberswere determined and the result is presented in table 4.17.

Table 4.16: Derived Strength Properties

S/No	Specimen No.	Tension Parallel to	Tension Perpendicular	Compression Parallel to Grain	Compression Perpendicular	Shear Strength (N/mm^2)

		Grain (N/mm^2)	to Grain (N/mm^2)	(N/mm^2)	to Grain (N/mm^2)	
1	E-1	46.6	7.6	35.5	40.2	6.5
2	E-2	63.5	5.3	40.7	28.5	8.3
3	E-3	58.0	5.9	39.1	31.4	7.8
4	E-4	48.4	7.7	36.1	41.1	6.7
5	E-5	61.0	6.5	40.0	34.8	8.1
6	E-6	83.3	7.5	46.0	39.9	10.4
7	E-7	71.0	6.0	42.8	32.0	9.1
8	E-8	65.9	6.2	41.4	33.3	8.6
9	E-9	64.0	7.3	40.9	38.8	8.4
10	E-10	75.0	8.7	43.9	46.2	9.5
11	E-11	70.5	7.3	42.7	38.8	9.1
12	E-12	71.8	7.3	43.1	39.1	9.2
13	E-13	51.5	6.0	37.1	32.1	7.0
14	E-14	56.9	6.2	38.8	33.1	7.6
15	E-15	85.0	5.8	46.5	30.7	10.5
16	E-16	79.2	5.9	45.0	31.3	9.9
17	E-17	60.5	6.9	39.9	36.9	8.0
18	E-18	72.9	8.1	43.3	42.9	9.3
19	E-19	70.5	5.7	42.7	30.6	9.1
20	E-20	85.6	6.8	46.6	36.3	10.6

Table 4.16: Derived Strength Properties (Contd.)

S/No	Specimen No.	Tension Parallel to	Tension Perpendicular	Compression Parallel to Grain	Compression Perpendicular	Shear Strength (N/mm^2)

		Grain (N/mm^2)	to Grain (N/mm^2)	(N/mm^2)	to Grain (N/mm^2)	
21	E-21	66.6	7.8	41.6	41.4	8.7
22	E-22	73.3	4.8	43.4	25.8	9.3
23	E-23	49.3	7.2	36.4	38.2	6.8
24	E-24	57.7	5.2	39.0	27.8	7.7
25	E-25	61.0	6.5	40.0	34.7	8.1
26	E-26	61.8	6.7	40.2	35.8	8.2
27	E-27	74.5	5.9	43.8	31.7	9.5
28	E-28	52.5	7.1	37.4	37.6	7.2
29	E-29	62.8	6.5	40.6	34.7	8.3
30	E-30	42.1	7.9	33.9	42.1	6.0
31	E-31	56.3	6.8	38.6	36.1	7.6
32	E-32	62.4	9.2	40.4	48.8	8.2
33	E-33	73.3	8.2	43.5	43.8	9.3
34	E-34	78.8	6.1	44.9	32.5	9.9
35	E-35	73.3	6.6	43.5	35.0	9.3
36	E-36	59.0	6.9	39.4	36.5	7.9
37	E-37	60.9	5.2	40.0	27.6	8.1
38	E-38	70.6	4.8	42.7	25.3	9.1
39	E-39	72.6	7.1	43.3	38.0	9.3
40	E-40	75.5	7.7	44.0	41.1	9.6

Table 4.17: Derived Stiffness Properties

S/No	Sample No	Tension Elastic Modulus Parallel to Grain	Tension Elastic Modulus	Shear Modulus (N/mm^2)

		(N/mm^2)	Perpendicular to Grain (N/mm^2)	
1	F-1	77.7	177.3	997.2
2	F-2	105.9	166.1	934.2
3	F-3	96.7	198.1	1114.4
4	F-4	80.7	216.7	1219
5	F-5	101.7	152.8	859.5
6	F-6	138.8	144.4	812.3
7	F-7	118.3	158.1	889.2
8	F-8	109.9	254.7	1432.5
9	F-9	106.6	221.2	1244.1
10	F-10	125.0	207.0	1164.5
11	F-11	117.6	221.2	1244.1
12	F-12	119.7	232.4	1307.2
13	F-13	85.8	166.1	934.2
14	F-14	94.8	106.2	597.3
15	F-15	141.7	232.4	1307.2
16	F-16	132.0	152.8	859.5
17	F-17	100.9	241.3	1357.3
18	F-18	121.5	169.6	954.3
19	F-19	117.6	138.3	778
20	F-20	142.7	166.1	934.2

Table 4.17: Derived Stiffness Properties (Continued)

S/No	Sample	Tension Elastic Modulus	Tension Elastic	Shear Modulus

	No	Parallel to Grain (N/mm^2)	Modulus Perpendicular to Grain (N/mm^2)	(N/mm^2)
21	F-21	111.0	189.9	1068.4
22	F-22	122.1	145.9	820.9
23	F-23	82.1	241.3	1357.3
24	F-24	96.1	160.2	901.2
25	F-25	101.7	237.2	1334.5
26	F-26	103.0	177.2	996.8
27	F-27	124.2	144.4	812.3
28	F-28	87.5	203.9	1147.1
29	F-29	104.7	142.6	802.1
30	F-30	70.2	177.3	997.2
31	F-31	93.9	200.2	1126.4
32	F-32	103.9	144.4	812.3
33	F-33	122.2	198.1	1114.4
34	F-34	131.3	187.3	1053.6
35	F-35	122.1	108.7	611.3
36	F-36	98.3	98.4	553.7
37	F-37	101.6	158.1	889.2
38	F-38	117.7	184.4	1037.4
39	F-39	121.0	174.5	981.5
40	F-40	125.8	189.9	1068.4

4.6 The Measured Stochastic Models

The coefficients of variations for the moisture contents, density, bending strength and modulus of elasticity were found to be 22%, 15%, 16% and 21% respectively. According to EN 384, the reference material properties are the most important properties upon which all, other properties are based. The high coefficients of variation obtained in this research confirmed that, the variability of the material properties of timber is not something to be ignored. This call for more rationale accommodation of uncertainties using the concepts of structural reliability.

4.7Strength Allocation Class for Terminalia ivorensis

The use of strength classes is intended to simplify the specification of timber, since it groups species in pre-defined categories. Characteristic values are taken from bending strength, bending stiffness and density. The allocation to a strength class is governed by the lowest strength class applicable to one of these properties.

The classification of the species into various hardwood strength classes was made using the characteristic bending strength, mean value of density and mean values of modulus of elasticity. The limiting values of the reference material properties from EN 338 (2009) are presented in Table 2.5, page 53 of literature review.

$$X_k = \mu - 1.65\sigma \qquad (4.13)$$

The measured and adjusted values of Terminalia ivorensis for bending strength, density and modulus of elasticity is as shown in table 4.18 below.

Table 4.18 Proposed Allocations of Strength Class for the *Terminalia ivorensis*

Reference Material Properties	12% Adjusted Values		Allocated Strength Class (EN 338, 2009)
	Mean Values	Characteristic Values	
Bending Strength (N/mm^2)	81.05	59.53	D18
Density (kg/m^3)	321.87	434.75	
Modulus of Elasticity (kN/mm^2)	13.18	7.45	

On considering tables 4.15 and the characteristic values of the density, bending strength and modulus of elastic obtained as $321.87kg/m^3$, $59.53N/mm^3$ and $7450.52N/mm^2$ respectively and using equation 4.1, from EN 384 (2004). The *Terminalia ivorensis* timber species was assigned to D18 timber strength in accordance with the class limits.

4.8 Developed Creep Deformation Models

The three *Terminalia ivorensis, timber* specimen (Sample A, Sample B and Sample C) were subjected to creep test for one year and the results are as shown in tables 3.6, 3.7 and 3.8. The creep deformation was plotted against time for all the three samples individually as well as combined with the average creep as shown Figure 4.21, 4.22, 4.23 and 4.24. It is clear from the plot that, Sample A displayed larger creep than Samples B and C, and Sample C has the least creep deformation at all age. The variability in the creep for the three samples is expected because the bending test results indicated that the

modulus of elasticity of the *Terminalia ivorensis* is a random with coefficient of variation of 21%.

The immediate impact of the applied load caused an initial type of deformation referred to as instantaneous creep. Instantaneous creep for sample A occurred at day five (5), that of sample B occurred at day fourteen (14) while that of samples C occurred at day four (4) with values of 2.5 X 10^{-4}, 6.0 X 10^{-4} and 2.0 X 10^{-4} respectively.

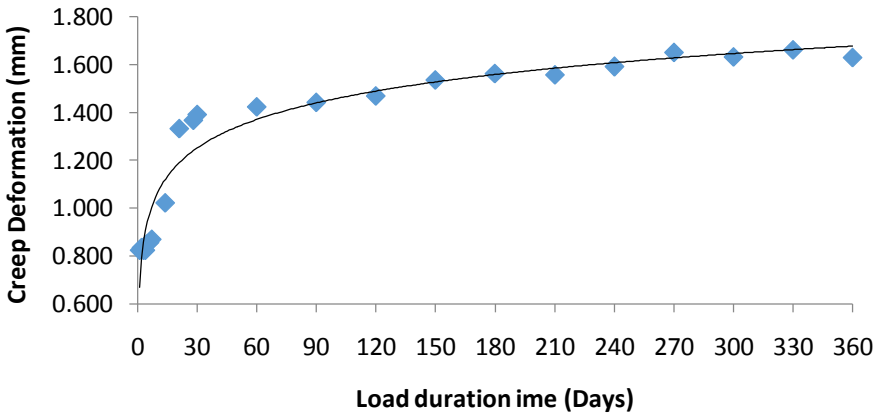

Figure 4.21: Creep deformation against load duration time for Sample A.

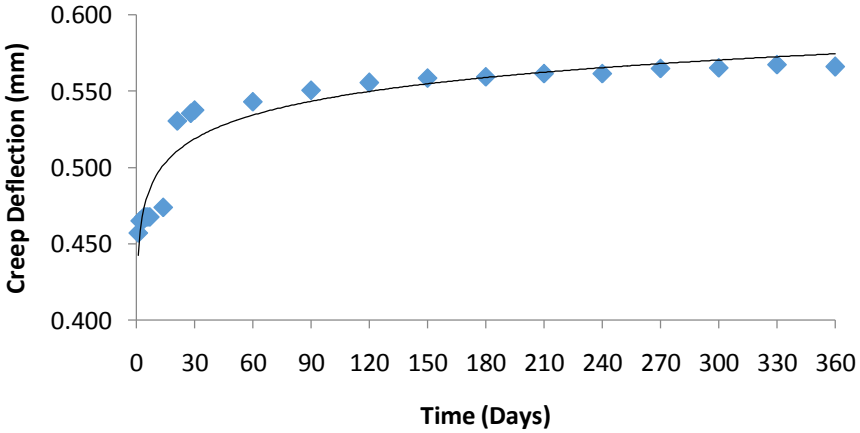

Figure 4.22: Creep deformation against load duration time for Sample B.

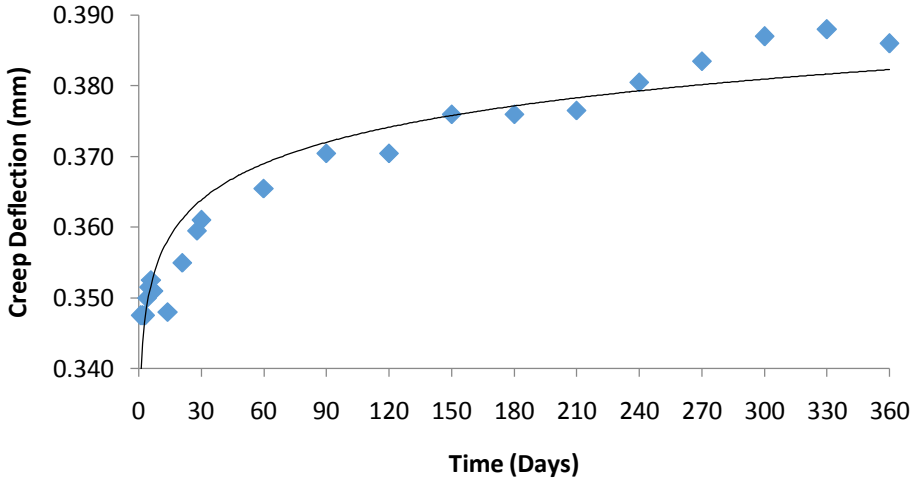

Figure 4.23: Creep deformation against load duration time for Sample C.

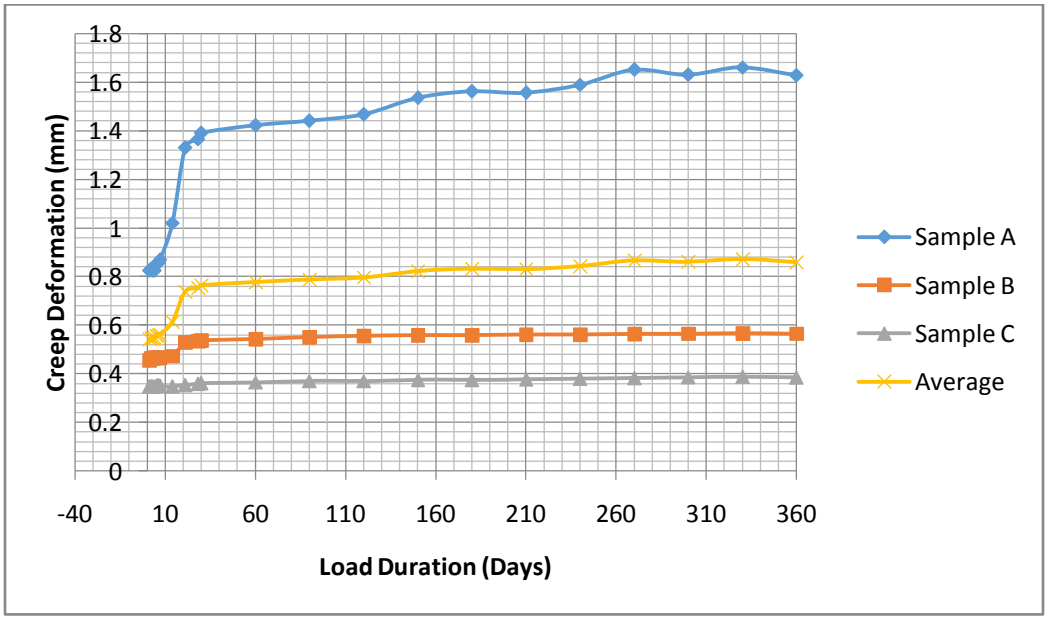

Figure 4.24: Plot of variation of creep deformation with time for the one-year creep test

The results presented in tables 3.6, 3.7 and 3.8 clearly depicted the nature of the generalized creep laws of materials presented in the literature. As observed from the plots the first characteristics of the creep time is the primary creep: which starts at a rapid rate. It is clear that between 0 to about 30 days' load duration, the *Terminalia ivorensis* passes through the primary stage of creep. Beyond 30 days, the creep rate slows with time. This is the secondary creep: it has a relatively uniform rate. The test conducted on the *Terminalia ivorensis* lasted for one year (360 days). After the secondary creep, the tertiary Creep set in: This has an accelerated creep rate and terminates when the material breaks or ruptures.

The creep data was plotted alongside the average as shown above, regression analysis was performed on the one-year creep deformation data, using Microsoft Excel. Linear regression model, exponential regression model as well as logarithmic prediction model for creep deformation for *Terminalia ivorensis*were developed as shown in Figure 4.25.

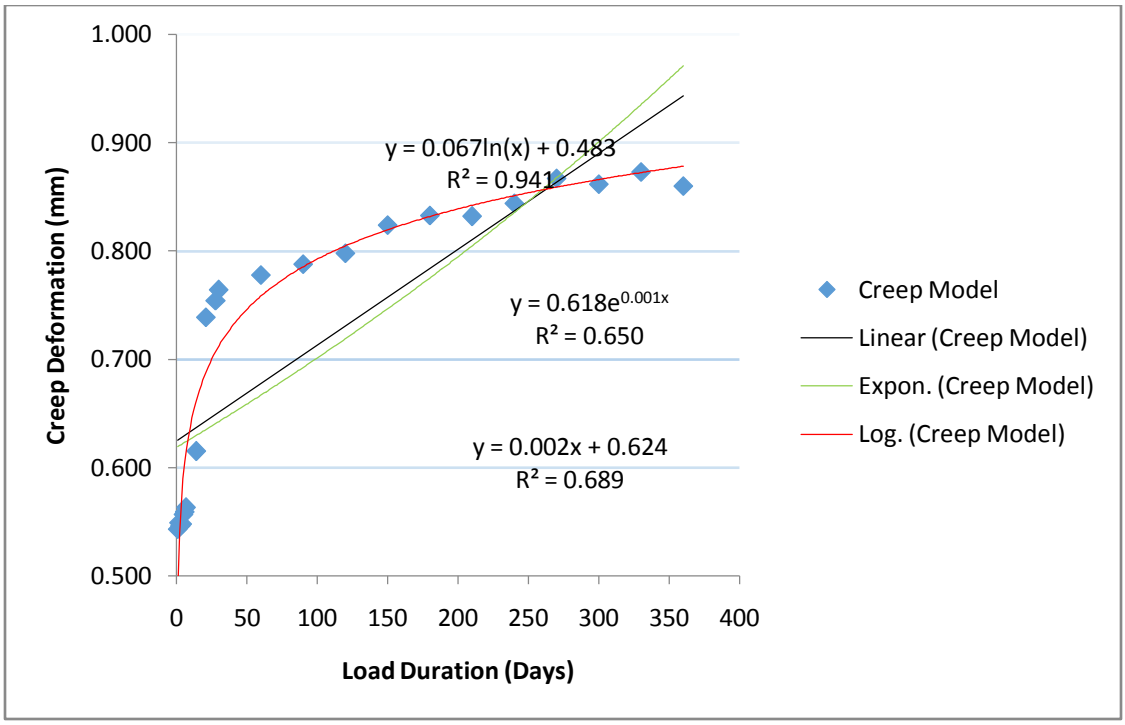

Figure 4.25: Regression analysis on creep data

As observed from the plot, the coefficients of determination are 0.689, 0.650 and 0.941 respectively for the linear, exponential and logarithmic models.

Based on the results presented in Figure 4.25, the developed linear, exponential and logarithmic creep deformation prediction models are given by equation 4.14, 4.15 and 4.16 respectively.

$$u_{creep} = 0.002(t) + 1.031 \qquad R^2 = 0.689 \qquad (4.14)$$

$$u_{creep} = 1.006\, e^{0.001x} \qquad R^2 = 0.650 \qquad (4.15)$$

$$u_{creep} = 0.170 \ln(t) + 0.670 \qquad R^2 = 0.941 \qquad (4.16)$$

Where;

u_{creep} is the creep deformation in mm and x is the sustained loading time in days.

The developed creep prediction models (Equation 4.14, 4.15 and 4.16) were used to predict the deformation of the timber specie (*Terminalia ivorensis*) for a one-year period. The predicted creep deformation based on the regression analysis were compared with the actual creep obtained from the laboratory as shown in Figure 4.26. The logarithmic prediction model has coefficient of determination of 0.941, followed by that of the linear model with coefficient of determination of 0.689. The exponential prediction model has the least coefficient of determination of 0.650. This indicates that the logarithmic model has the highest level of acceptability with strong correlation between the creep deformation and the time of sustained loading.

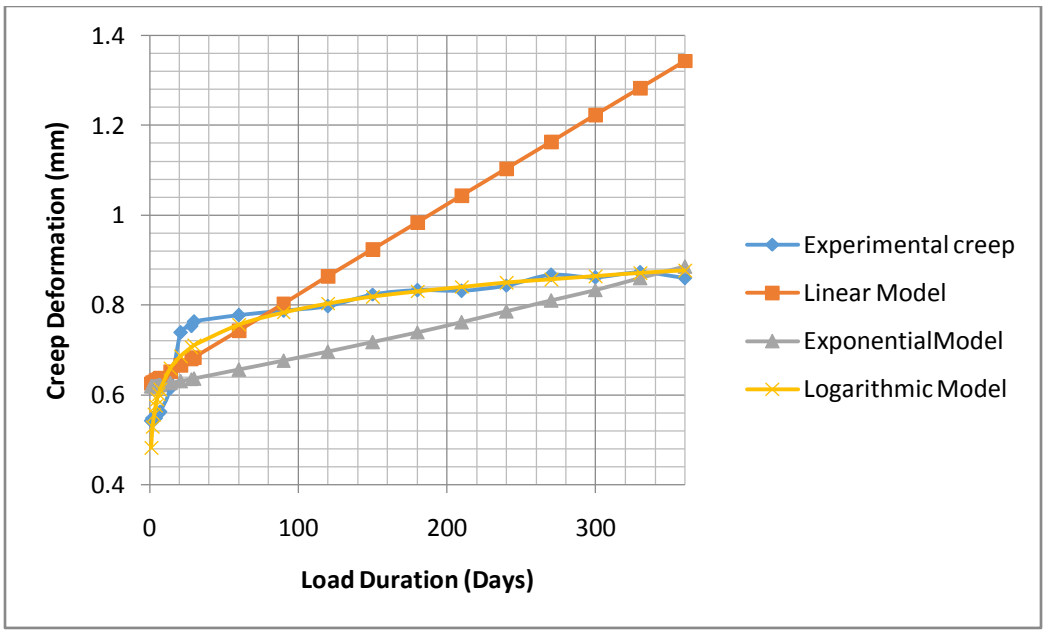

Figure 4.26: Comparison of predicted and observed creep

The percentage prediction error throughout the period of investigation was found to be very high for the linear prediction model and least for the logarithmic prediction model. Considering the value of the coefficient of determination and the percentage prediction

errors it is concluded here that logarithmic model is the best and recommended for use in the determination of creep deformation of timber members made with *Terminalia ivorensis*.

The result of percentage error analysis is presented in appendix C

4.9 Microstructure of *Terminalia ivorensis* Timber

Plates IItoV show the longitudinal sections for *Terminalia ivorensis* cell before and after compression creep at 1000 x and 1500 x magnifications, obtained from scanning electron microscopy (SEM). On observation of plate II and IV which are the microstructural arrangements of the specimen before creep deformation at 1000x and 1500x magnifications, it could be seen that the green arrows indicate vessel cells and red arrow points to parenchyma cells (darker areas that surround vessels). Blue arrow points to fiber cells (lighter areas).

After compression creep test at1000x and 1500x magnifications respectively as observed in plate III and V. There are no visible vessel cells in the section; they are all closed. The yellow arrows in the images indicate more compact cellular structure of the wood fiber.

This is attributed to the densification (closure) of the timber due closure of the empty cells due to compressive loading. During densification, the cellular structure of wood is permanently packed together.

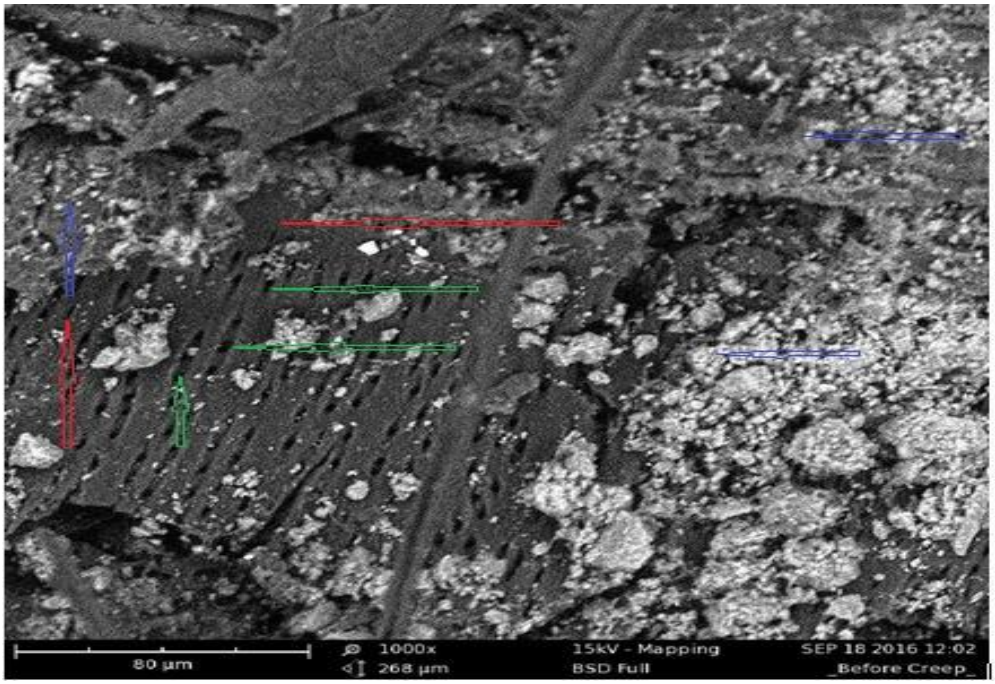

Plate II: Microstructure of the longitudinal section of *Terminalia ivorensis* timber before creep (1000x magnification)

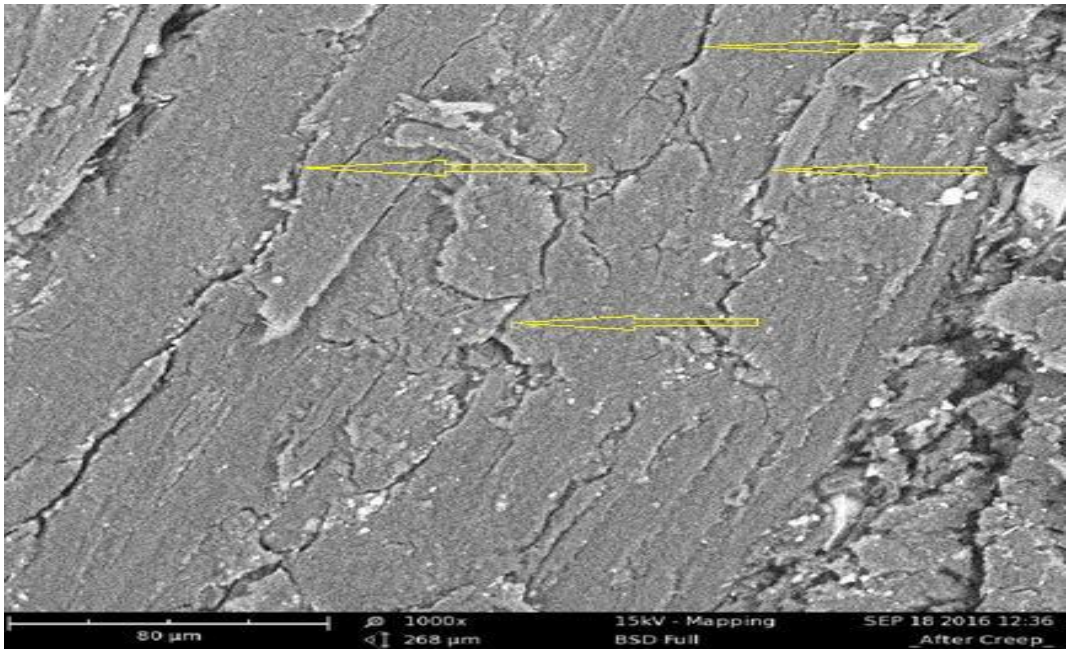

Plate III: Microstructure of the longitudinal section of *Terminalia ivorensis* timber after creep (1000x magnification)

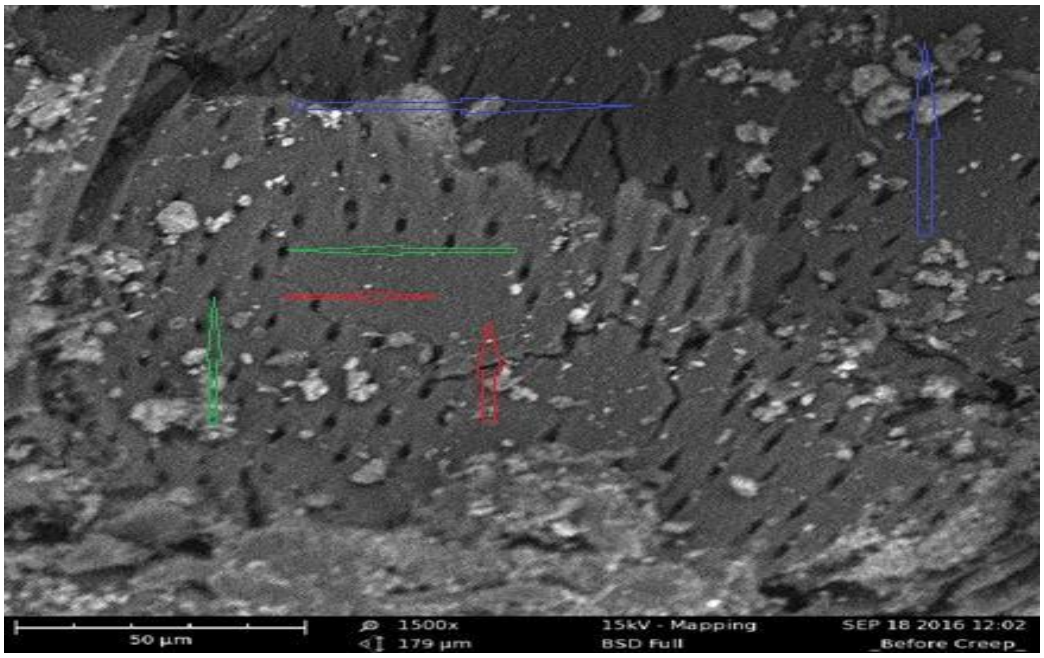

Plate IV: Microstructure of the longitudinal section of *Terminalia ivorensis* timber before creep (1500x magnification).

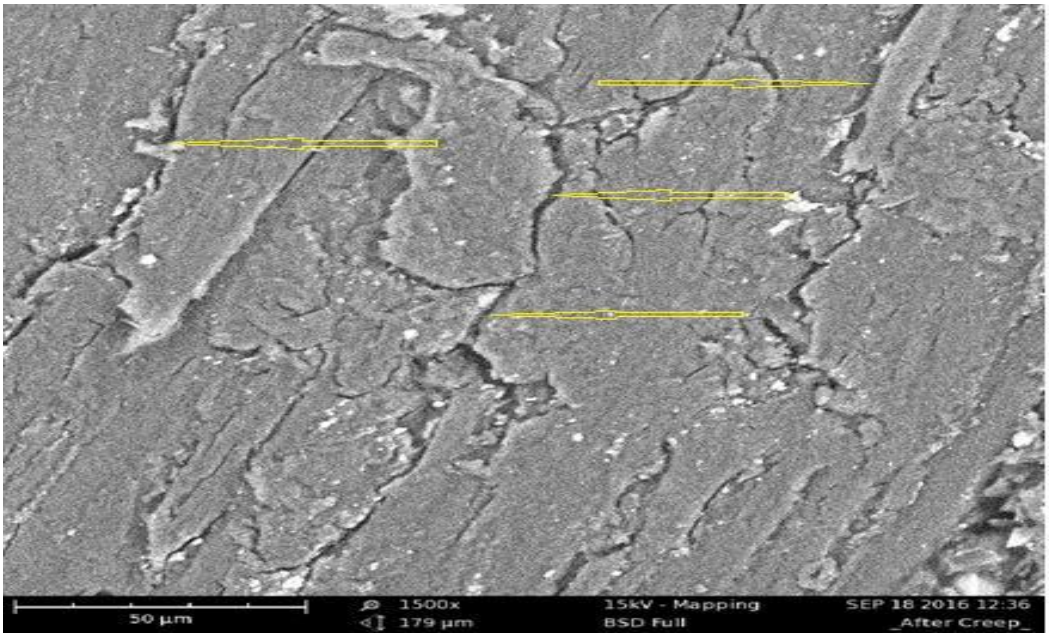

Plate V: Microstructure of the longitudinal section of *Terminalia ivorensis* timber after creep (1500x magnification).

The general explanation on the densification observed from the microscopic analysis could be explained with reference to what is presented in the literature as follows:

When compressed transversely, a honeycomb pattern of wood will first deform elastically. Following the elastic deformation, cell walls will begin to buckle, causing cell layers to cave in on themselves. When cells collapse, the inner walls will come in self-contact, causing an increase in stiffness. The load-displacement curve will then begin linearly, followed by a strain-hardening region where strain increases with little increase in stress caused by (caused by cell wall buckling). After the strain-hardening, a further increase in stiffness can sometimes be noticed, which is caused by self-contact in the cells (Kettunen, 2009).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the creep behavior of Black Afara(*Terminalia ivorensis)* timber was presented. Based on the results obtained from the material properties tests, creep deformation tests and elemental analysis, the following conclusions are made

1. The coefficients of variations for the moisture contents, density, bending strength and modulus of elasticity were found to be 22%, 15%, 16% and 21% respectively. According to EN 384, the reference material properties are the most important properties upon which all, other properties are based.
2. It was also established in this study that, the appropriate distribution models for density, bending strength and modulus of elasticity are Normal, Weibull and Lognormal respectively. The determination of the appropriate distribution models for random variable is one of the vital organs of structural reliability.
3. Based on the data on the reference material properties of *Terminalia ivorensis* timber species determined in this study, the timber species was classified into D18 strength class based on EN 338 (2009) European timber strength classification system.
4. From fitting of creep data to linear, exponential and logarithmic regression models. The coefficients of determination for each of the model was determined. The logarithmic model showed the highest correlation between the creep deformation and load duration. The coefficient of determination (R^2)

was measured as 0.941 (94%). This implied that, logarithmic regression model is the most appropriate. The selection of the logarithm models was buttressed by the values obtained from regression modelling error analysis, which shows the least deviation of the predicted creep deformation from the measured creep deformation. The time-dependent creep deformation model developed in this study is recommended for use in determining creep deformation at any age of timber life in service instead of the single value specified by Eurocode 5 for ranges of timing.

5. From microstructure analysis conducted before and after creep deformation,the result of the analysis revealed that, the cellular structure contains voids which were found to have closed after creep deformation. This implies that, the application of the long term loading lead to the closure of the voids within the cells microstructure, leading to the densification of the timber.

5.2 Recommendations

Based on the conclusions of the study, the following recommendations were made;

1. The statistical models for the reference material properties (bending strength, modulus of elasticity and density) determined in this study as well as their fitted distribution models are recommended for use in reliability based design of timber structural members with *Terminalia ivorensis* timber species in order to fully accommodate uncertainties associated with its material properties.

2. The study recommends the use of the developed creep deformation models in the accurate prediction of the rheology of *Terminalia ivorensis* timber specie, especially when conducting serviceability limit state analysis.

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APPENDICES

Appendix A: Density and Moisture Content of the Forty Member *Terminalia ivorensis*

Table A1: Density and Moisture Content of the *Terminalia ivorensis*

S/No	Bulk Weight (g)	Oven Dry Weight (g)	Moisture Content (%)	Depth (mm)	Thickness (mm)	Width (mm)	Density (kg/m^3)
1	102.0	87.8	16.2	76	50	46	502.3
2	77.9	68.3	14.2	75	49	52	356.4
3	72.8	63.0	15.5	75	49	43	392.3
4	64.4	57.5	12.1	70	51	31	514.2
5	86.4	73.9	16.9	72	50	47	434.7
6	80.4	71.6	12.3	70	52	40	499.0
7	87.0	74.4	16.8	74	50	51	400.3
8	87.2	71.8	21.4	72	50	48	415.9
9	79.6	67.1	18.6	74	51	37	485.6
10	73.4	61.0	20.4	71	49	30	577.7
11	84.5	73.9	14.3	74	49	42	484.6
12	104.8	87.4	19.9	70	49	52	489.1
13	68.7	58.0	18.5	77	50	37	401.0
14	103.5	89.3	15.8	72	49	61	413.3
15	88.5	76.5	15.6	73	49	55	384.2
16	85.3	68.8	24.0	77	51	45	390.9
17	105.7	91.4	15.7	78	50	51	461.4
18	86.2	73.6	17.1	77	51	35	536.8
19	65.2	55.4	17.7	79	50	37	382.8
20	72.1	61.3	17.5	77	51	35	453.6

Table A1 (Contd.): Density and Moisture Content of the *Terminalia ivorensis*

S/No.	Bulk Weight (g)	Oven Dry Weight (g)	Moisture Content	Height (mm)	Thickness (mm)	Width (mm)	Density (kg/m^3)
21	89.8	72.1	24.6	78	51	35	517.8
22	80.5	64.0	25.8	75	50	53	322.7
23	112.4	93.2	20.6	78	50	50	477.6
24	114.4	91.4	25.2	76	49	70	347.4
25	83.8	67.0	25.1	71	50	44	433.7
26	82.2	70.6	16.5	74	51	42	447.0
27	71.6	61.2	17.0	79	51	38	395.7
28	90.6	78.0	16.2	73	50	45	470.6
29	88.0	73.6	19.7	82	51	40	433.4
30	78.7	67.8	16.0	76	51	34	525.9
31	73.2	63.4	15.5	77	48	38	451.9
32	78.6	65.7	19.7	73	50	29	610.1
33	95.0	76.9	23.5	72	50	39	547.2
34	91.7	77.3	18.6	71	50	53	406.3
35	95.2	80.6	18.1	74	49	51	437.6
36	78.5	69.0	13.7	75	51	40	456.7
37	64.8	55.0	17.8	74	50	44	344.6
38	84.9	77.5	9.4	78	49	64	316.7
39	92.6	77.6	19.4	80	51	40	474.8
40	81.6	73.1	11.6	68	51	41	514.4

Appendix B: Least Square Regression Plots for the Four-Pont Bending Test

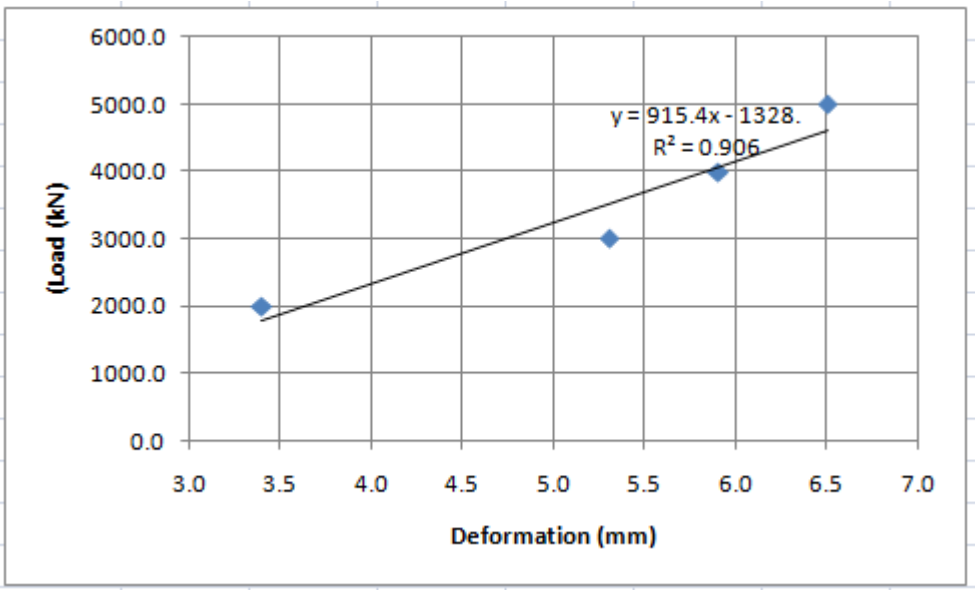

Figure B1: Least Square Regression Plot for Member 1

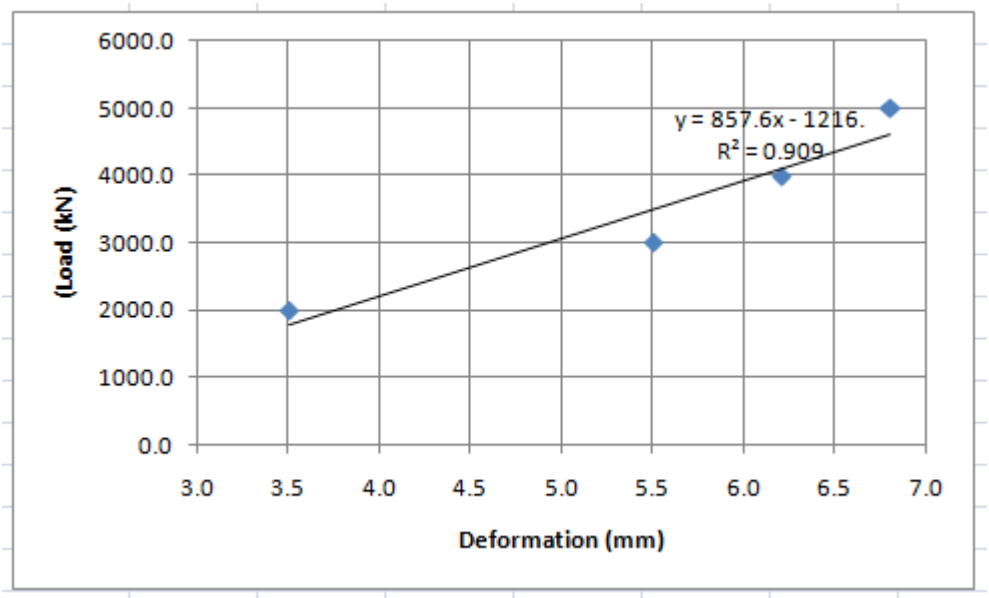

Figure B2: Least Square Regression Plot for Member 2

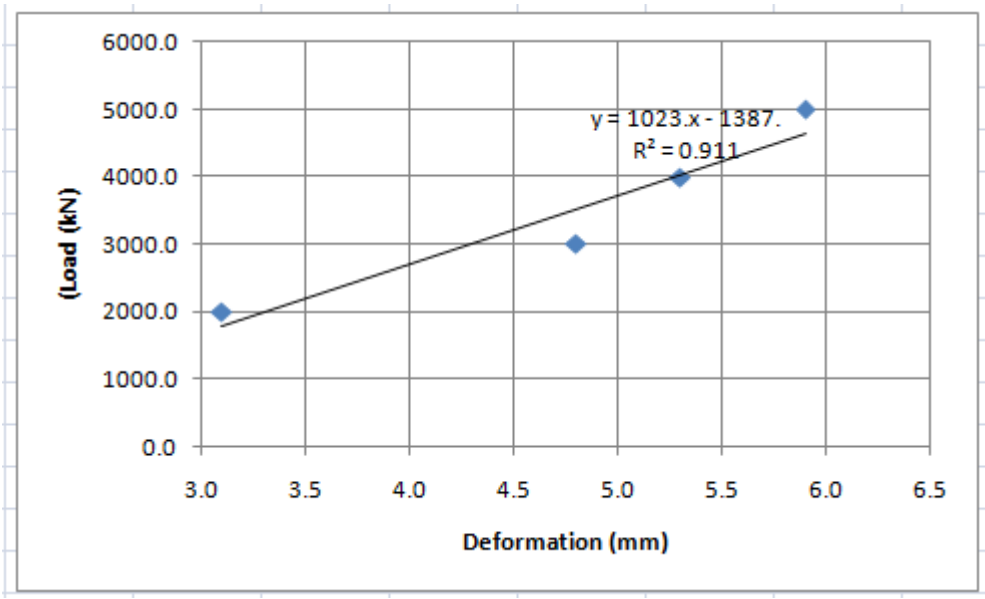

Figure B3: Least Square Regression Plot for Member 3

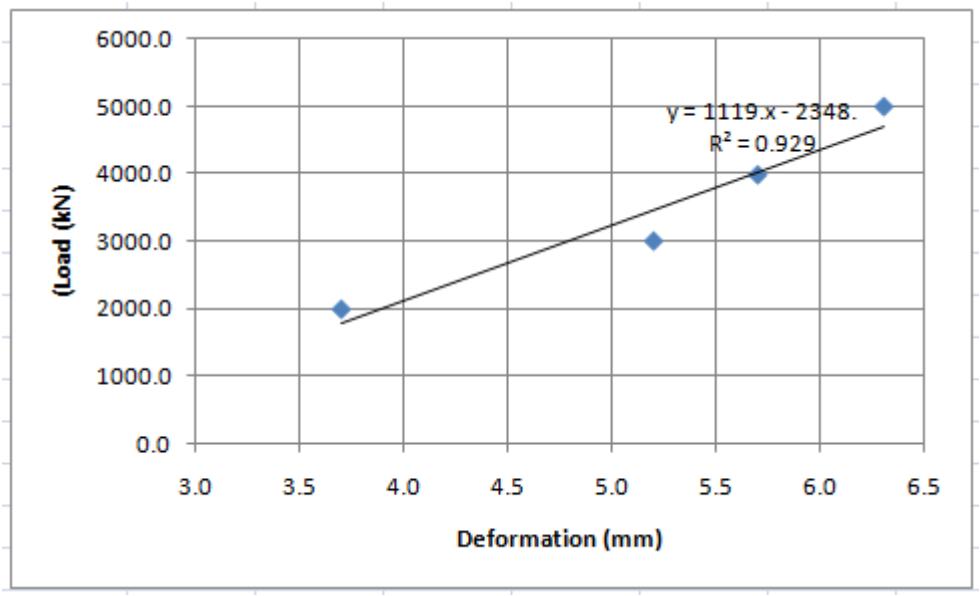

Figure B4: Least Square Regression Plot for Member 4

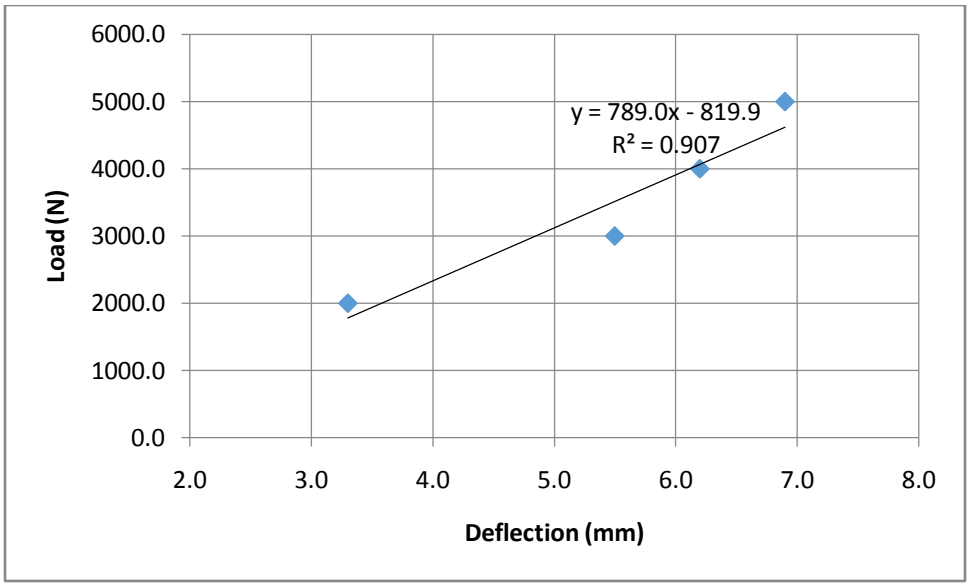

Figure B5: Least Square Regression Plot for Member 5

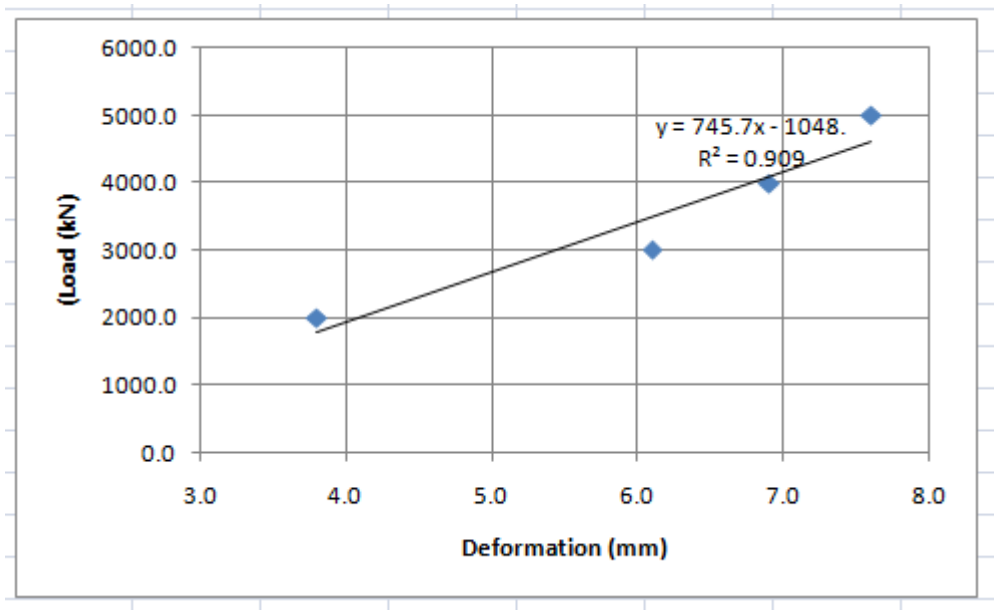

Figure B6: Least Square Regression Plot for Member 6

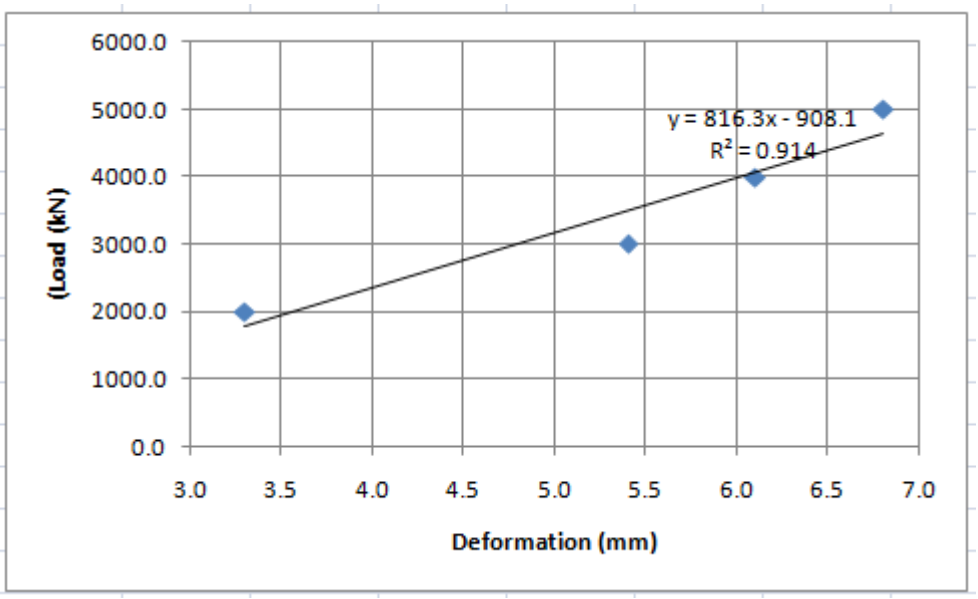

Figure B7: Least Square Regression Plot for Member 7

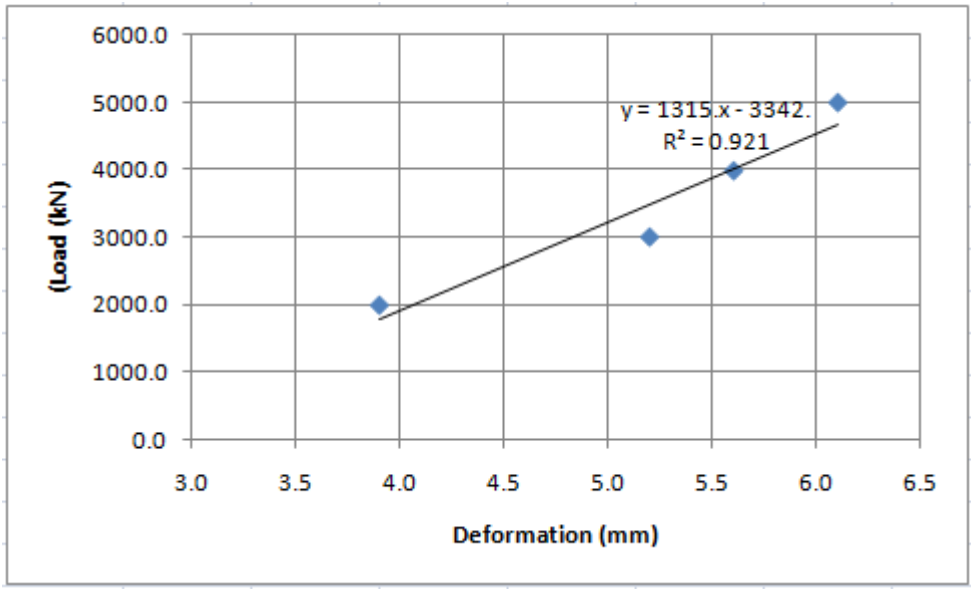

Figure B8: Least Square Regression Plot for Member 8

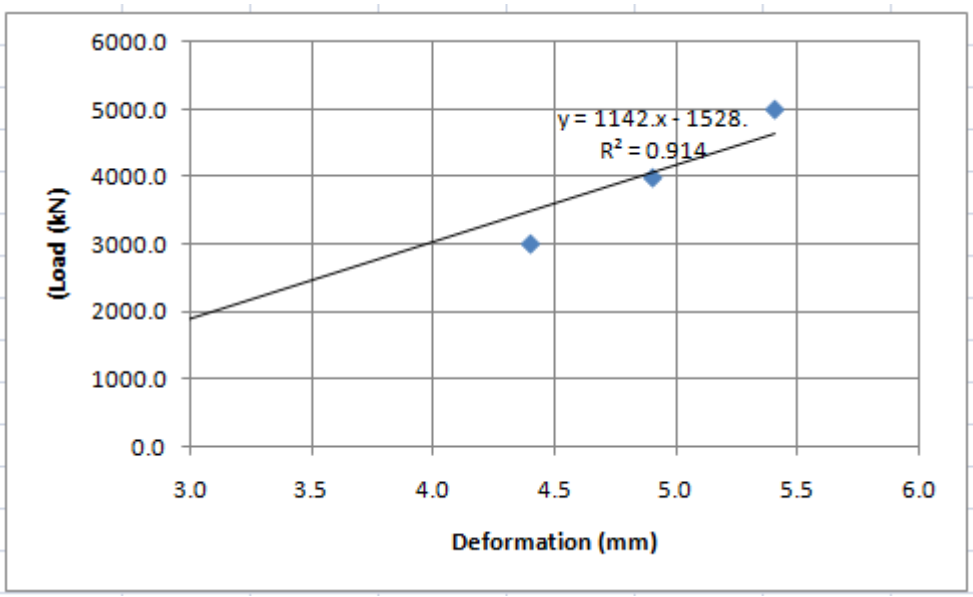

Figure B9: Least Square Regression Plot for Member 9

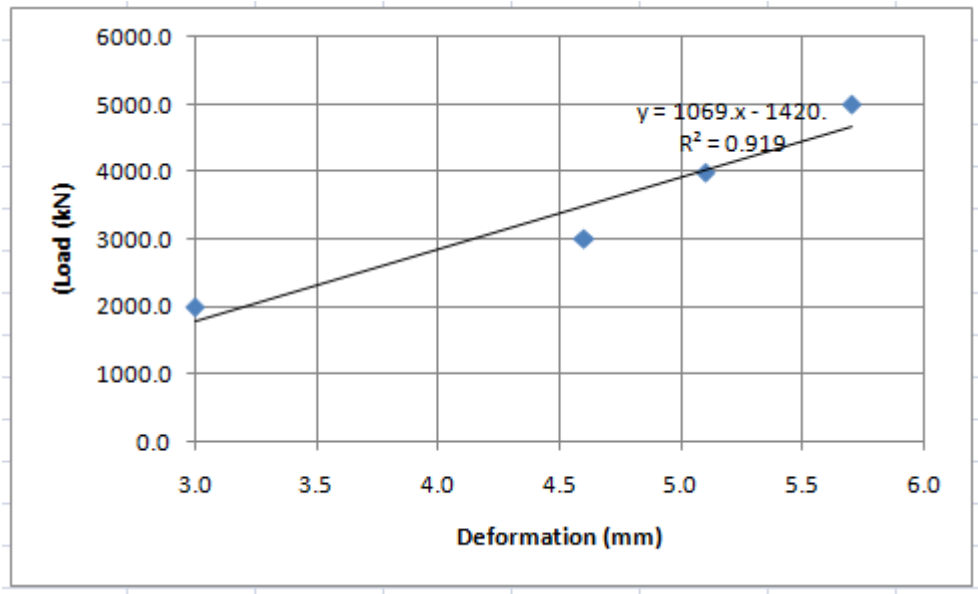

Figure B10: Least Square Regression Plot for Member 10

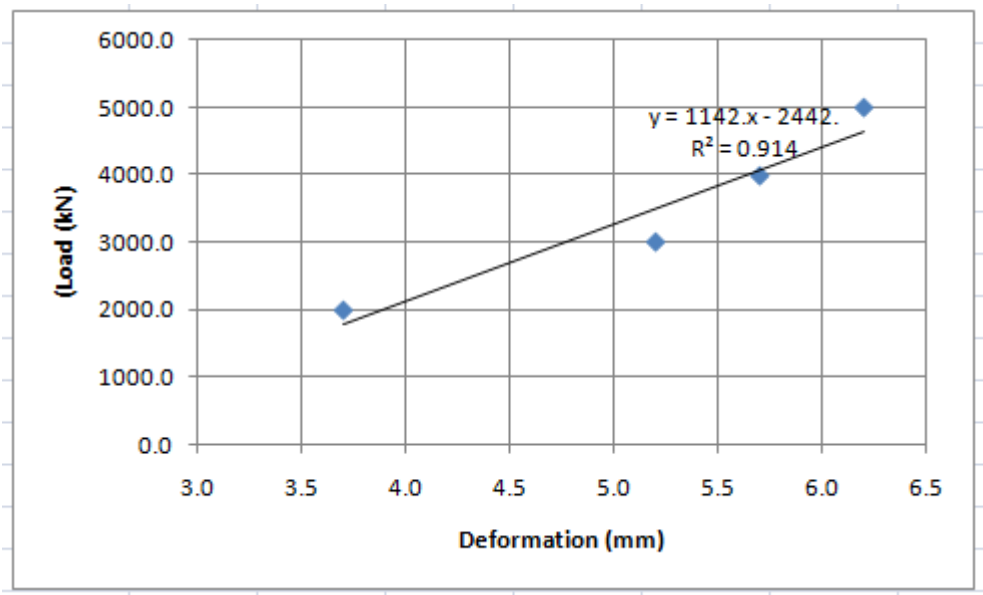

Figure B11: Least Square Regression Plot for Member 11

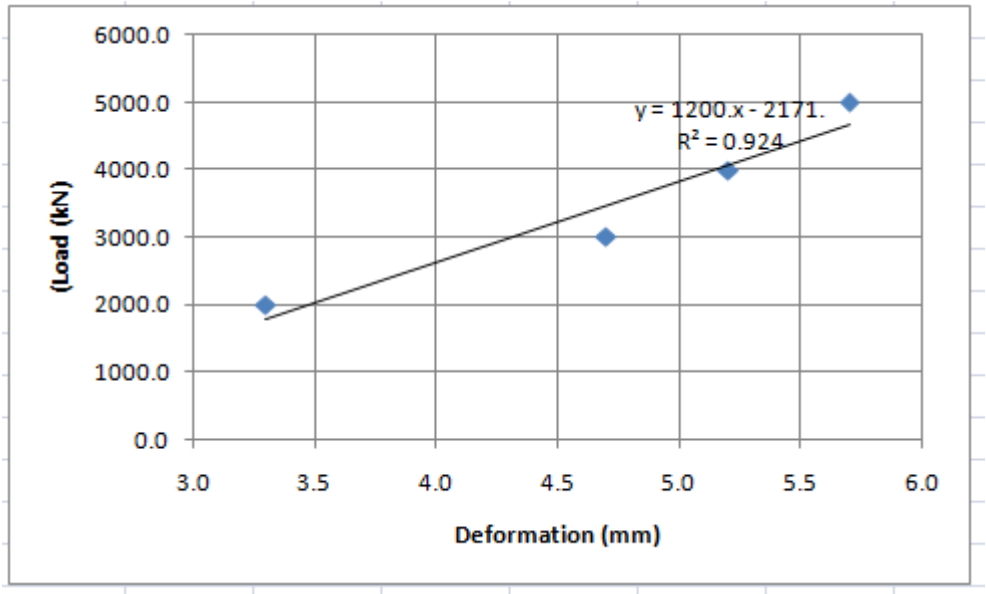

Figure B12: Least Square Regression Plot for Member 12

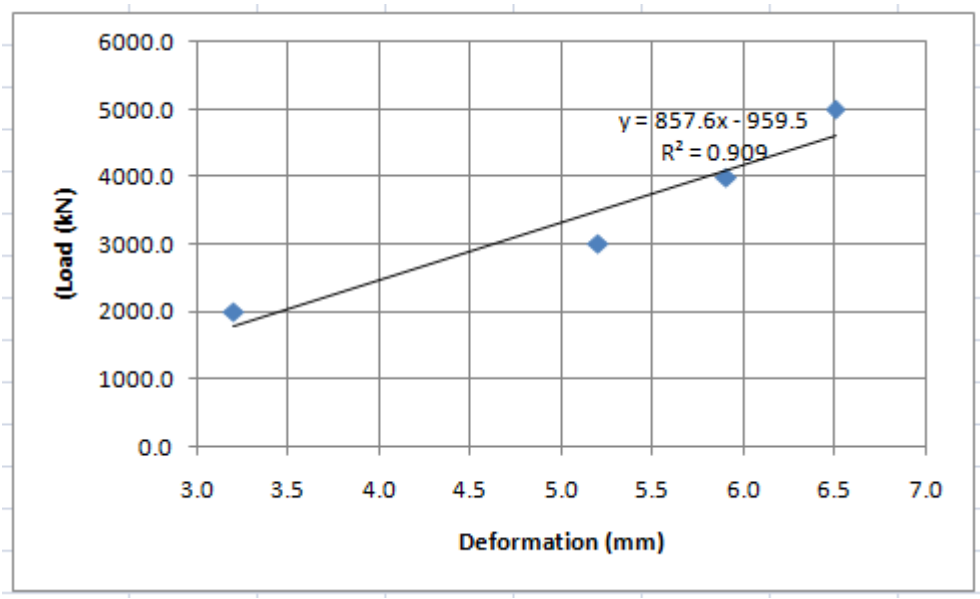

Figure B13: Least Square Regression Plot for Member 13

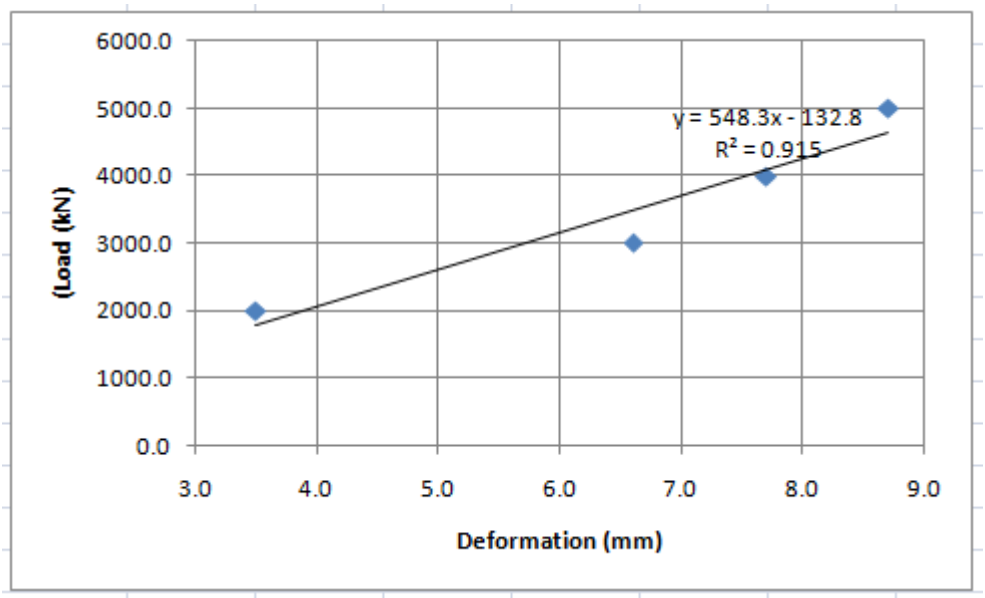

Figure B14: Least Square Regression Plot for Member 14

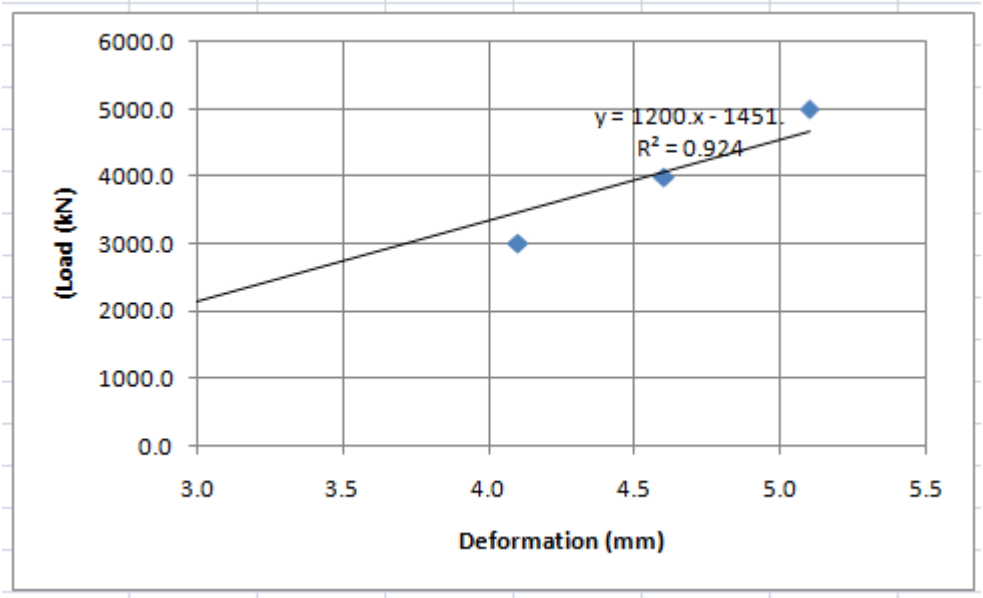

Figure B15: Least Square Regression Plot for Member 15

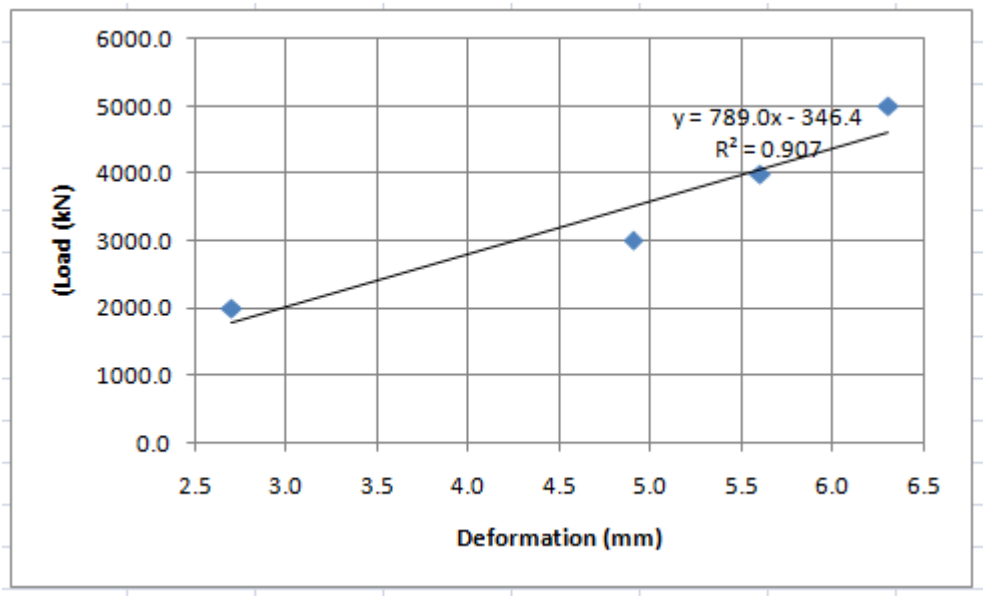

Figure B16: Least Square Regression Plot for Member 16

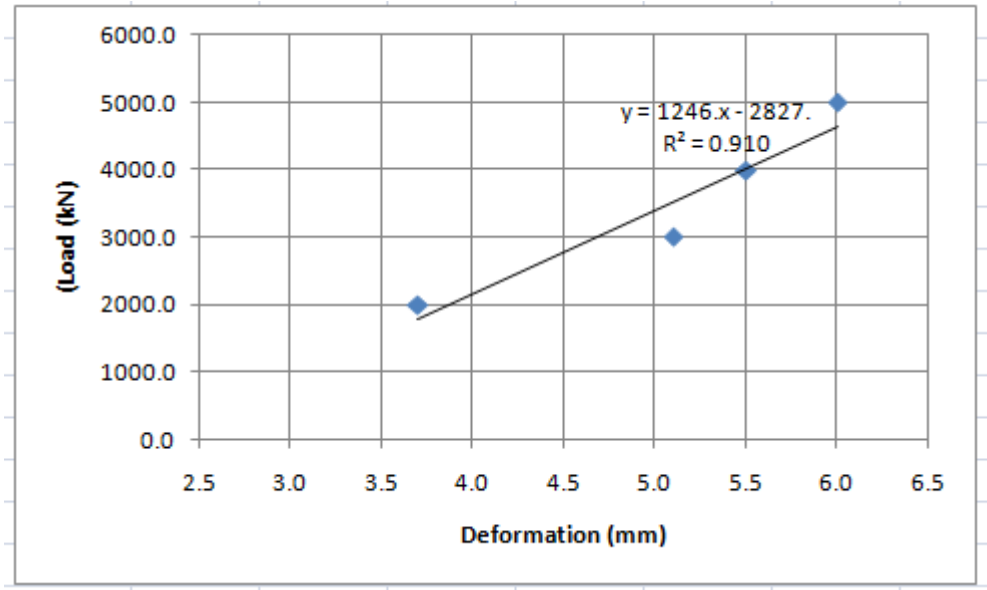

Figure B17: Least Square Regression Plot for Member 17

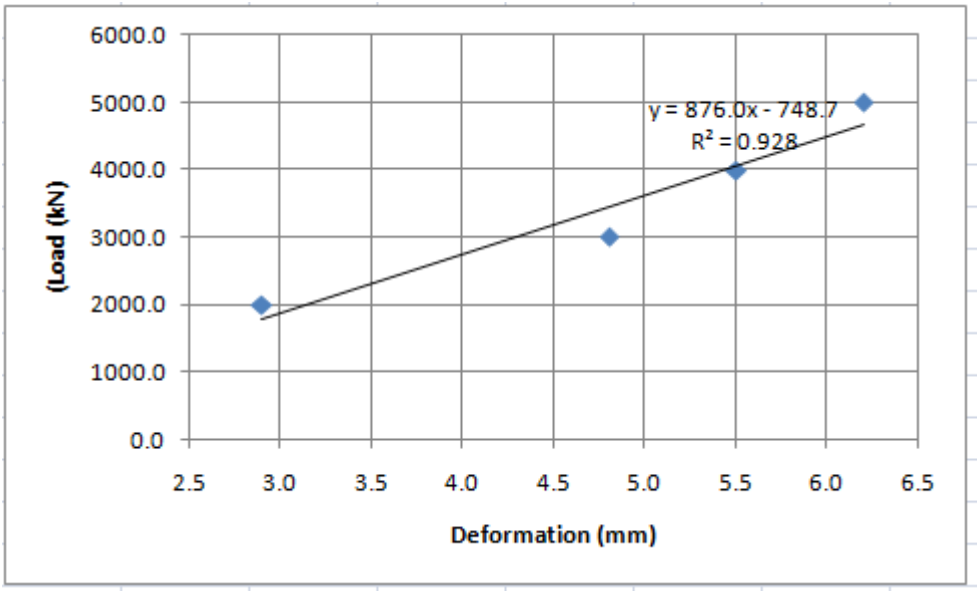

Figure B18: Least Square Regression Plot for Member 18

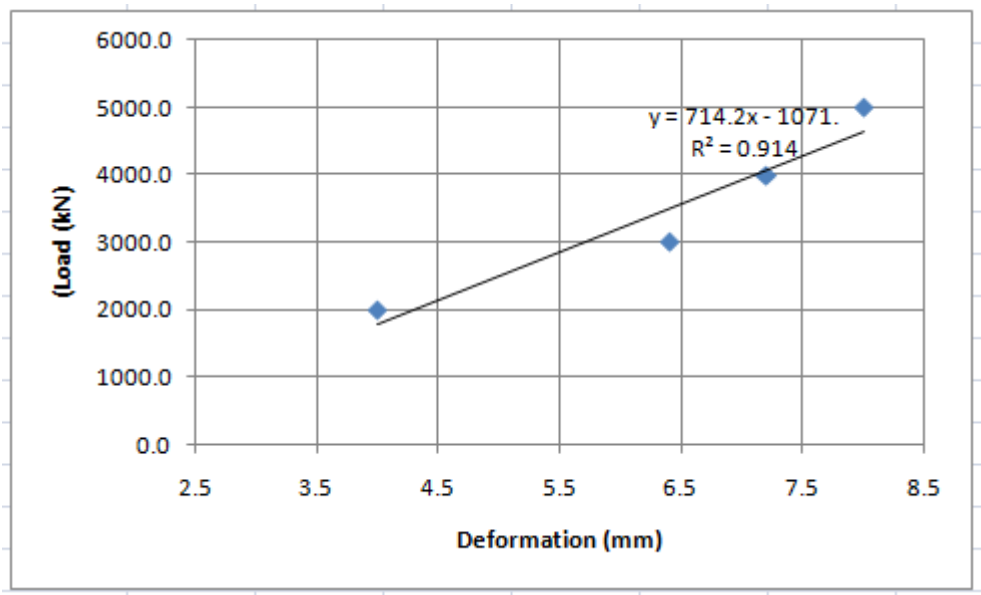

Figure B19: Least Square Regression Plot for Member 19

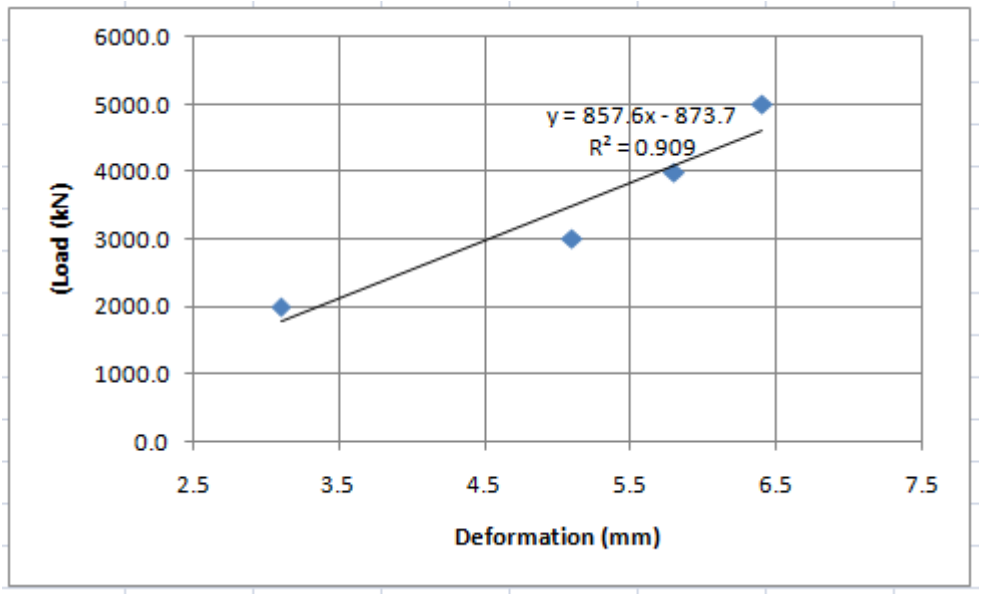

Figure B20: Least Square Regression Plot for Member 20

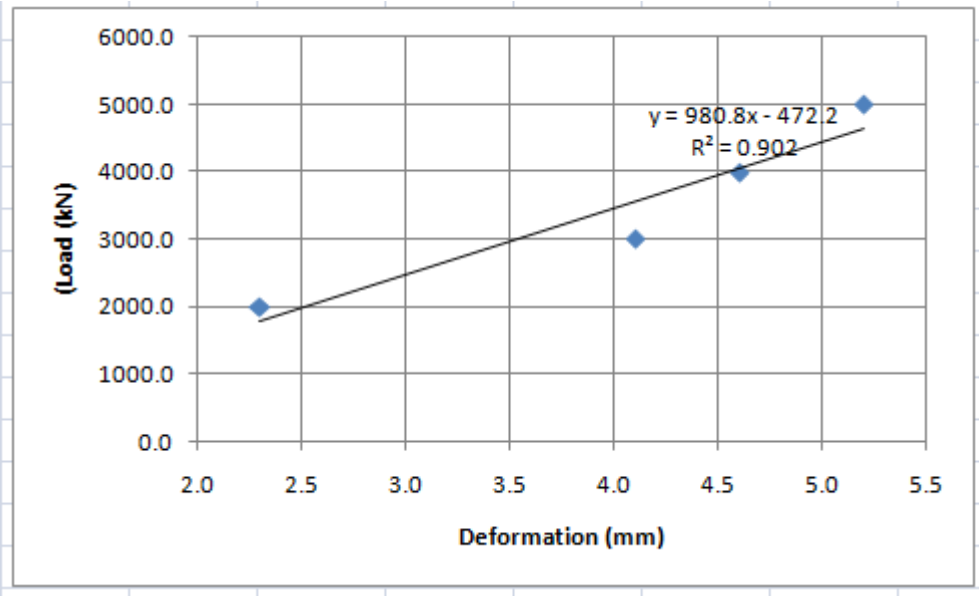

Figure B21: Least Square Regression Plot for Member 21

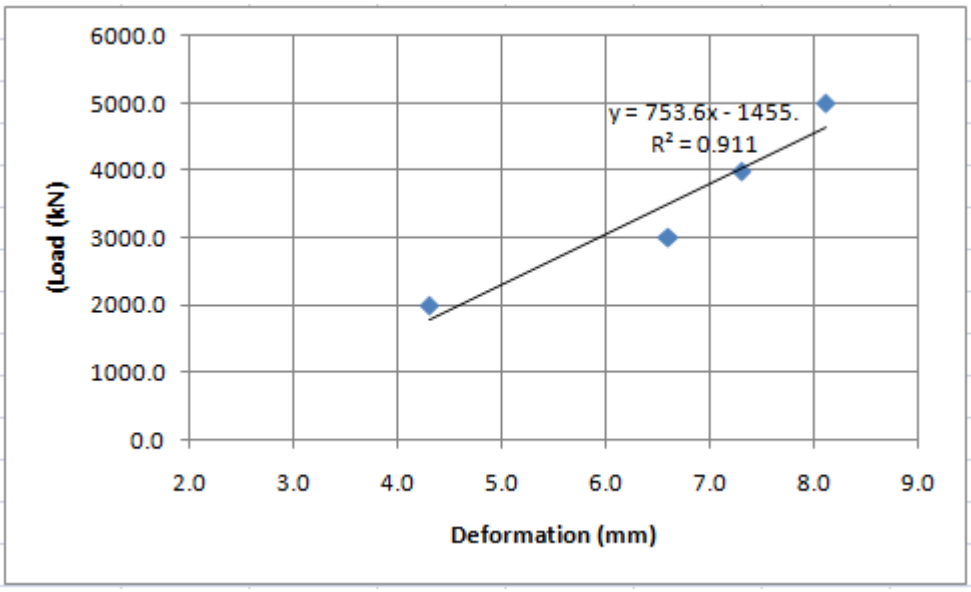

Figure B22: Least Square Regression Plot for Member 22

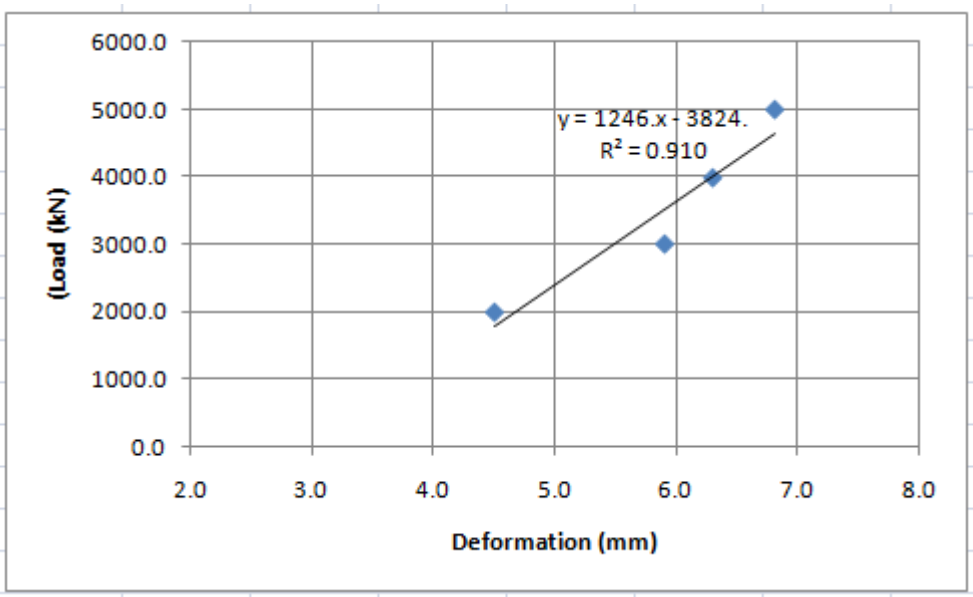

Figure B23: Least Square Regression Plot for Member 23

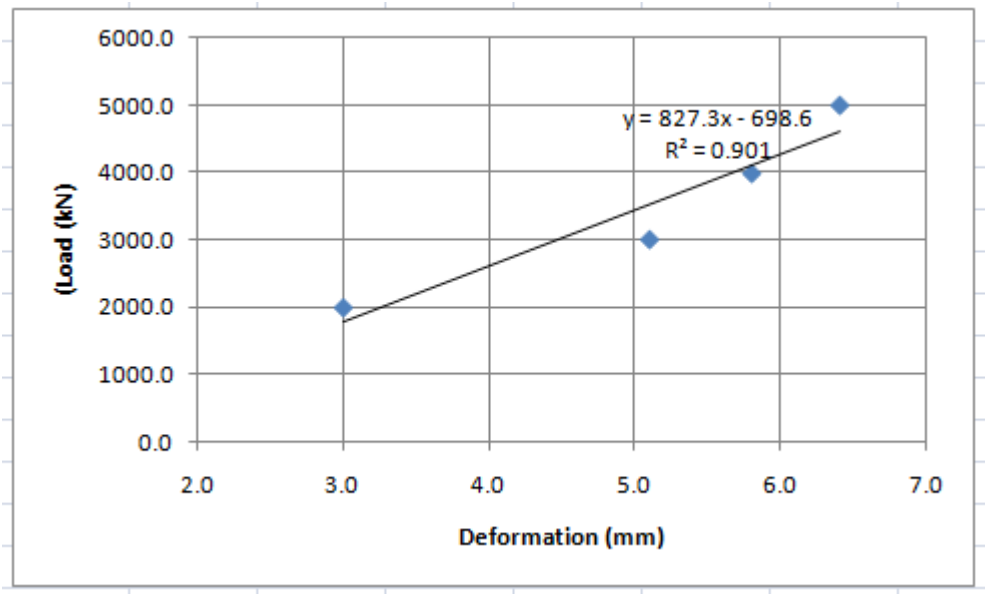

Figure B24: Least Square Regression Plot for Member 24

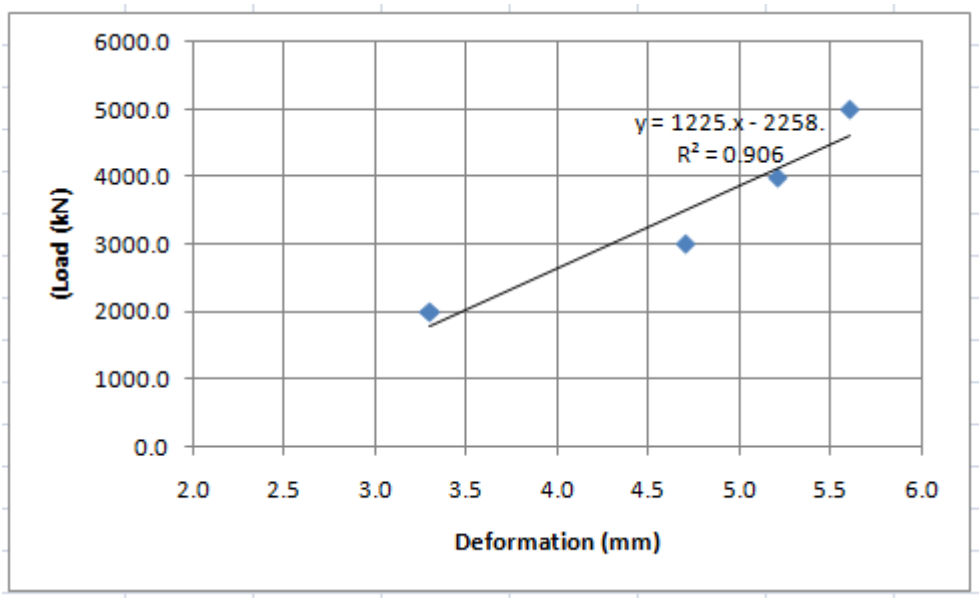

Figure B25: Least Square Regression Plot for Member 25

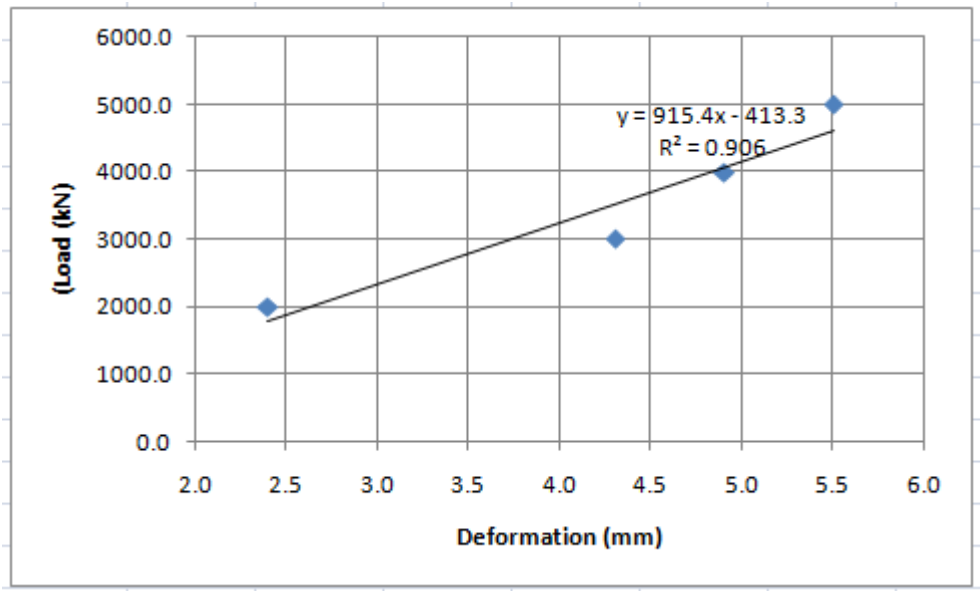

Figure B26: Least Square Regression Plot for Member 26

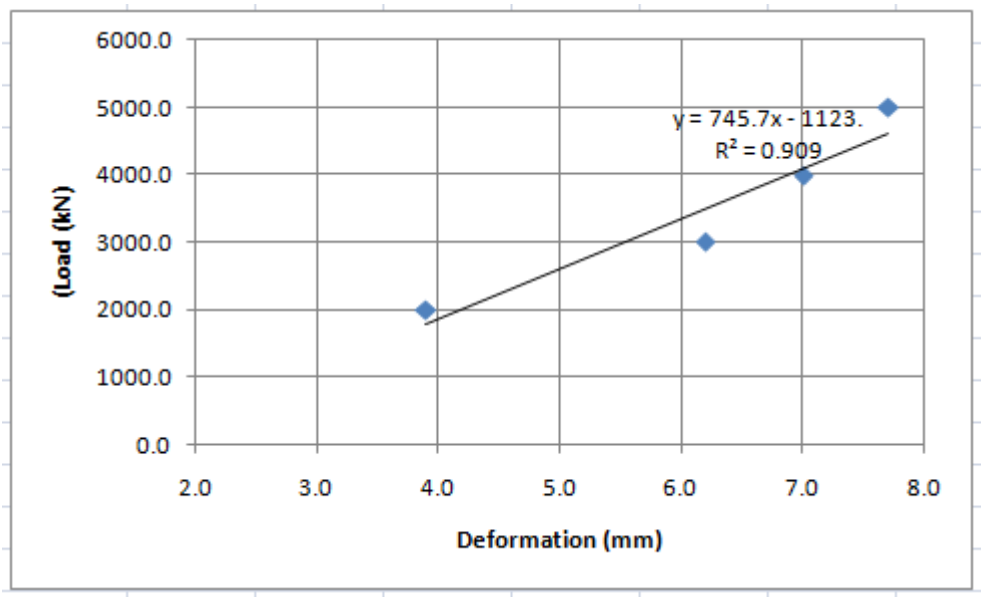

Figure B27: Least Square Regression Plot for Member 27

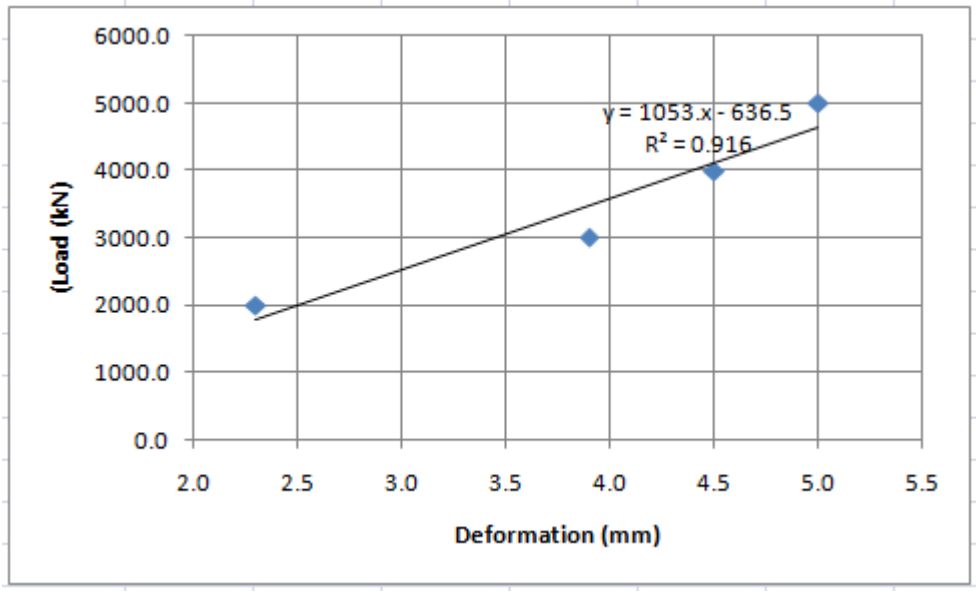

Figure B28: Least Square Regression Plot for Member 28

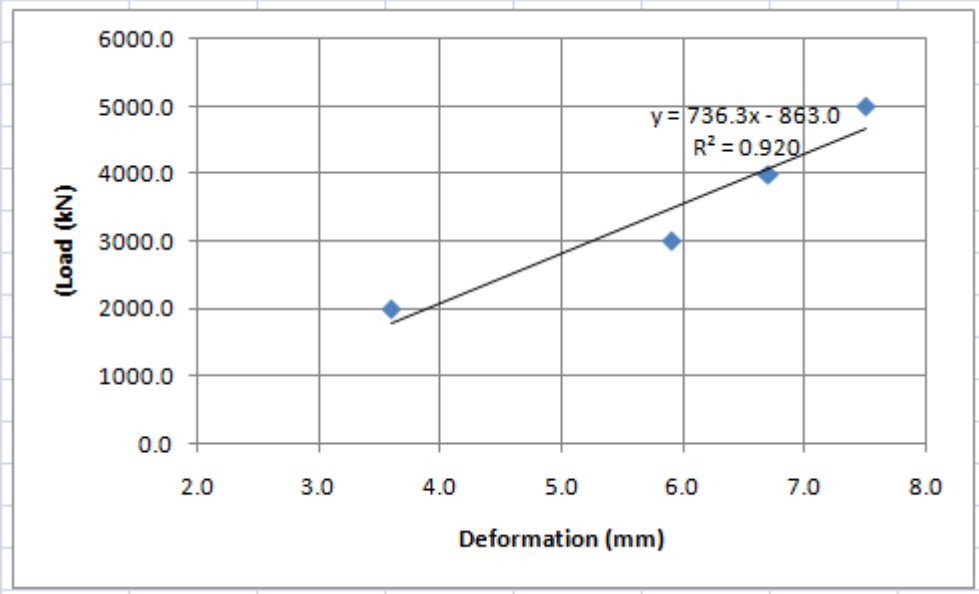

Figure B29: Least Square Regression Plot for Member 29

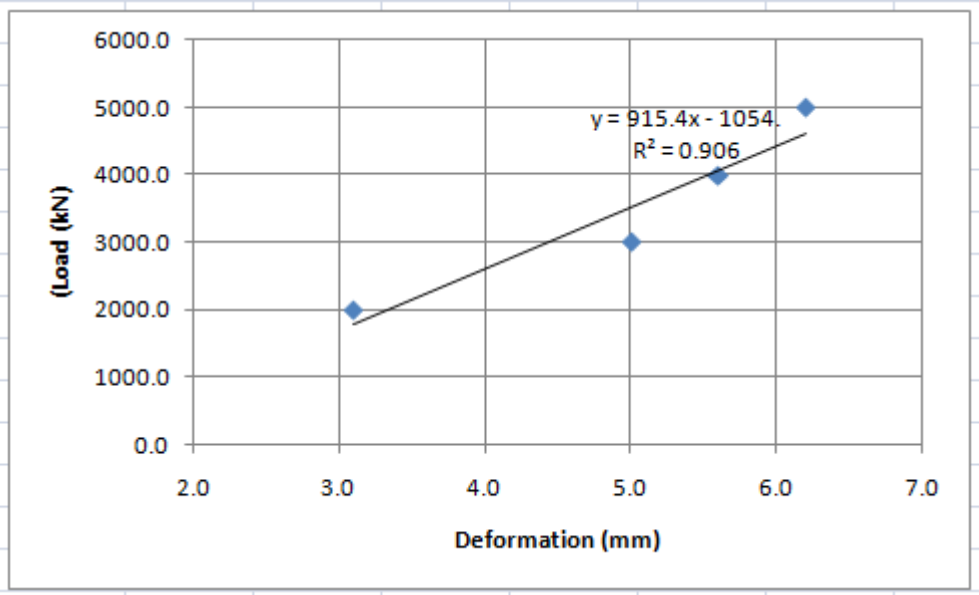

Figure B30: Least Square Regression Plot for Member 30

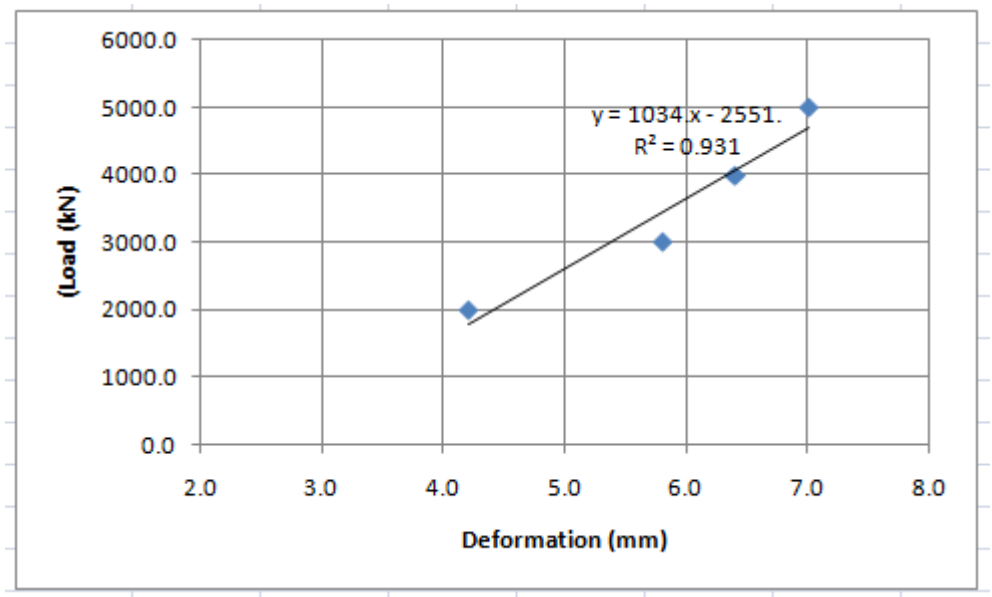

Figure B31: Least Square Regression Plot for Member 31

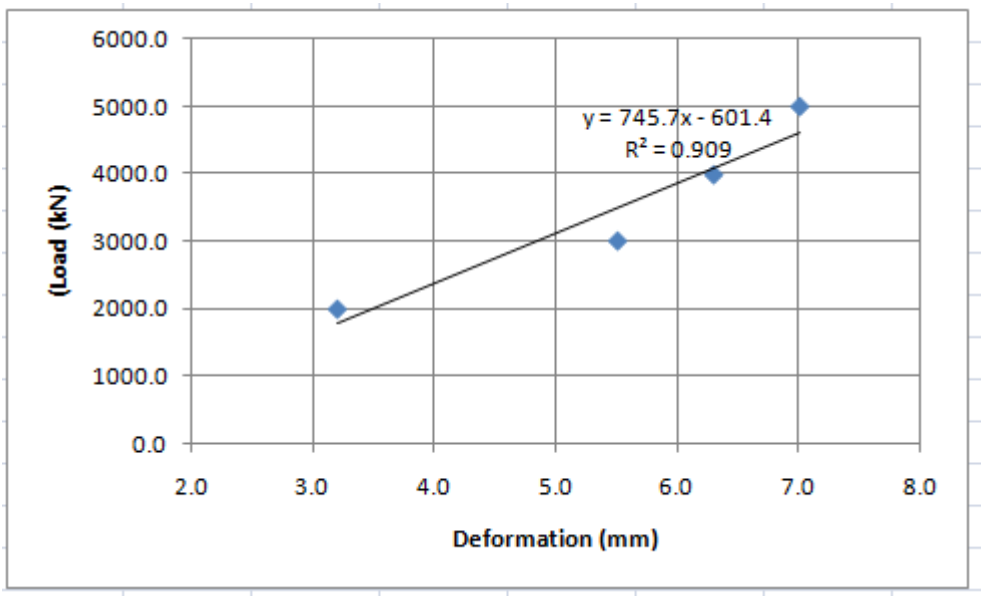

Figure B32: Least Square Regression Plot for Member 32

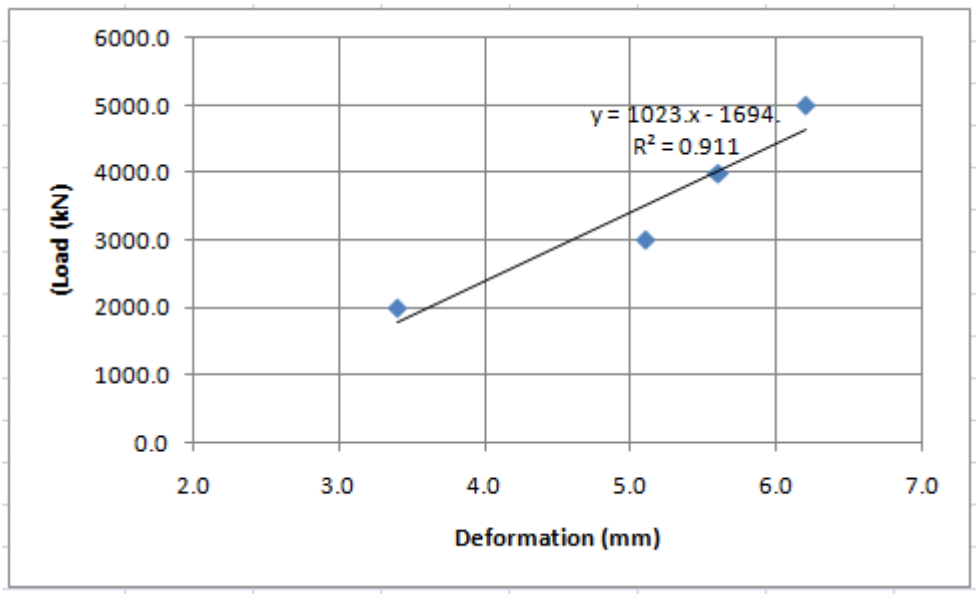

Figure B33: Least Square Regression Plot for Member 33

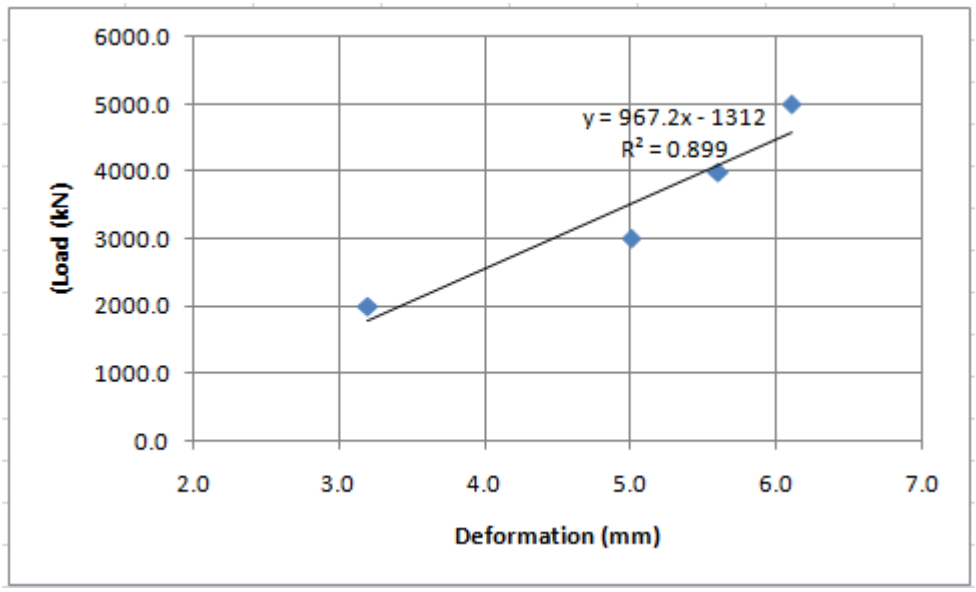

Figure B34: Least Square Regression Plot for Member 34

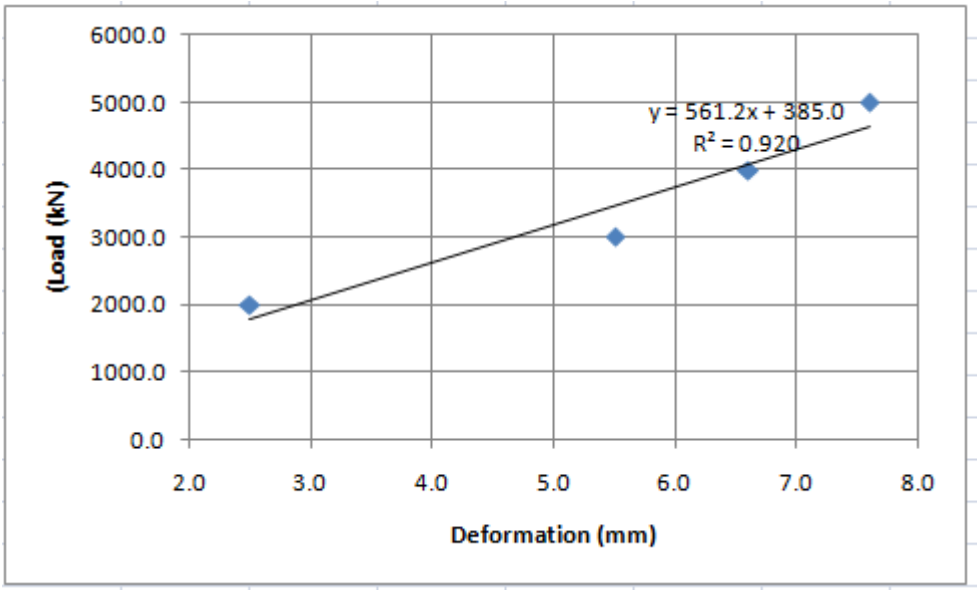

Figure B35: Least Square Regression Plot for Member 35

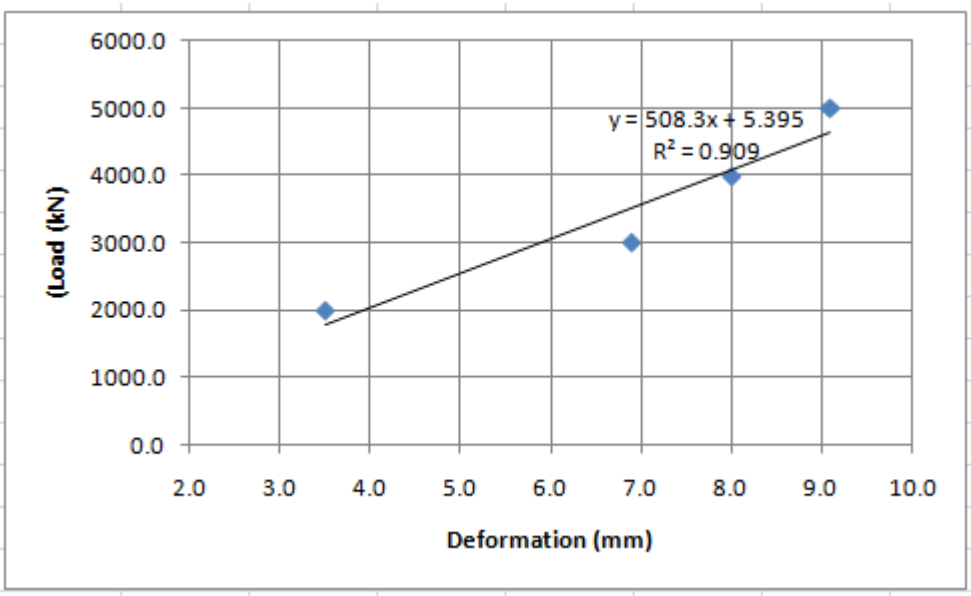

Figure B36: Least Square Regression Plot for Member 36

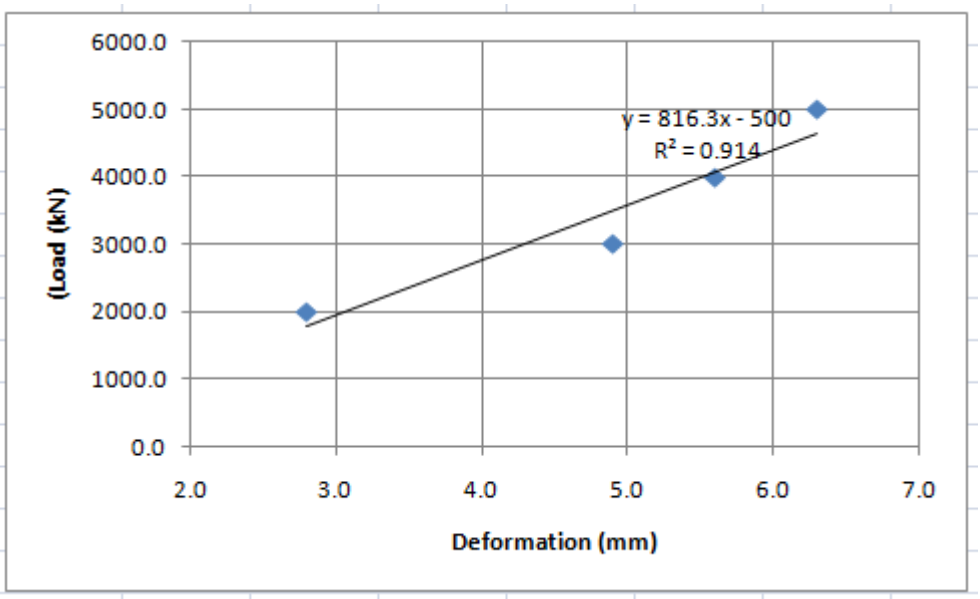

Figure B37: Least Square Regression Plot for Member 37

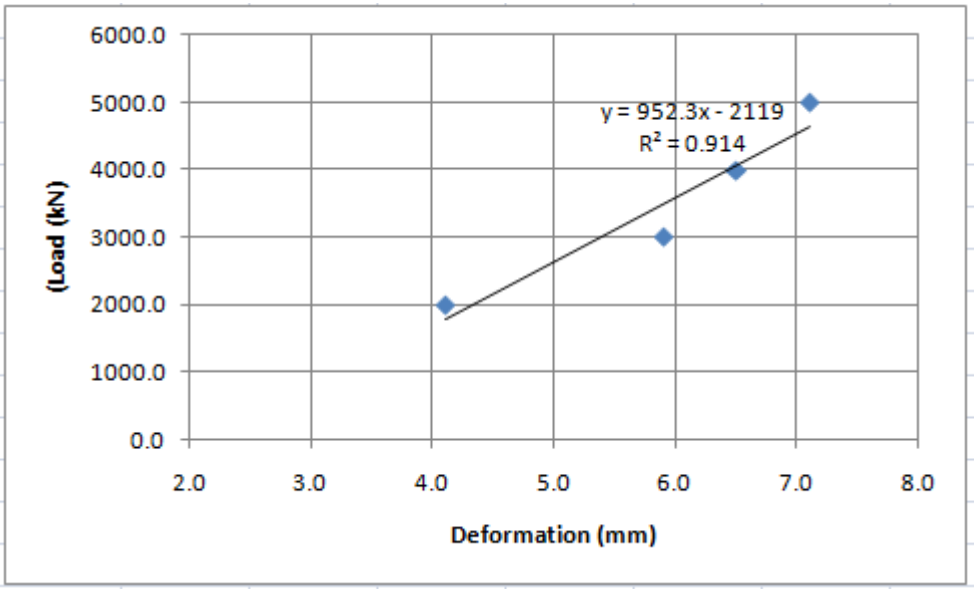

Figure B38: Least Square Regression Plot for Member 38

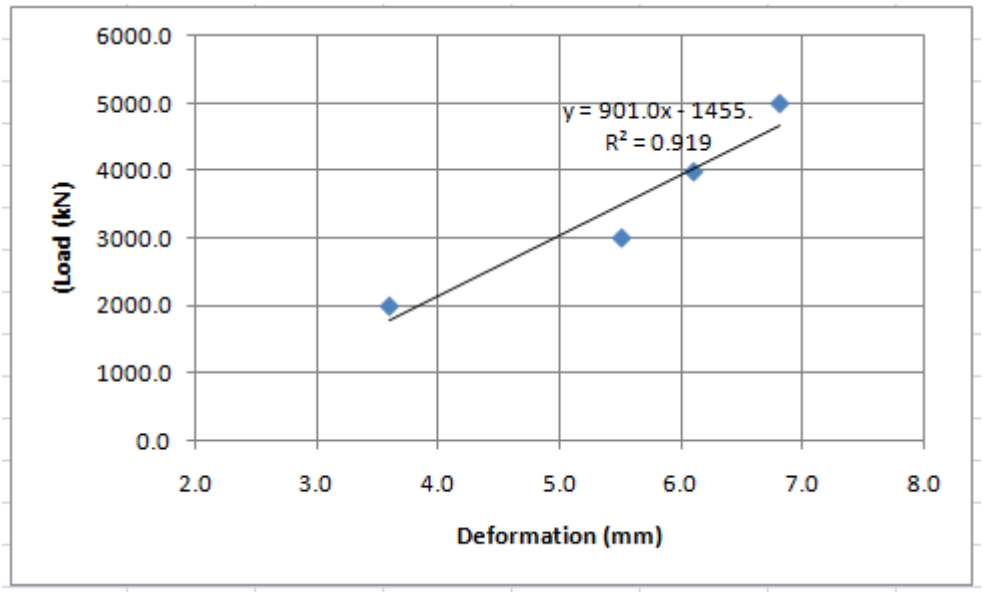

Figure B39: Least Square Regression Plot for Member 39

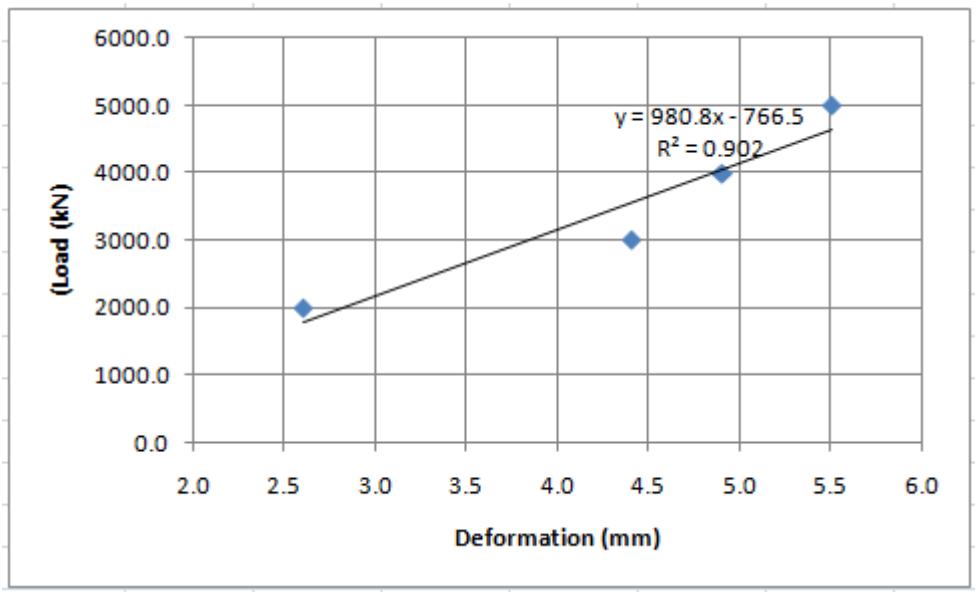

Figure B40: Least Square Regression Plot for Member 40

Appendix C: Error Analysis of the Test and Predicted Results

Time (Days)	Experimental Creep	Linear Creep Model	Exponential Creep model	Logarithmic Creep Model`	Model Prediction Error (%)		
					Linear	Exponential	Logarithmic
1	0.543	0.626	0.619	0.483	15.285	13.926	11.050
2	0.549	0.628	0.619	0.529	14.390	12.794	3.563
3	0.546	0.630	0.620	0.557	15.385	13.527	1.943
4	0.548	0.632	0.620	0.576	15.328	13.226	5.088
5	0.557	0.634	0.621	0.591	13.824	11.508	6.074
6	0.559	0.636	0.622	0.603	13.775	11.220	7.880
7	0.563	0.638	0.622	0.613	13.321	10.540	8.948
14	0.615	0.652	0.627	0.660	6.016	1.905	7.287
21	0.739	0.666	0.631	0.687	9.878	14.599	7.039
28	0.754	0.680	0.636	0.706	9.814	15.710	6.332
30	0.764	0.684	0.637	0.711	10.471	16.646	6.953
60	0.778	0.744	0.656	0.757	4.370	15.654	2.658
90	0.788	0.804	0.676	0.784	2.030	14.188	0.446
120	0.798	0.864	0.697	0.804	8.271	12.683	0.722
150	0.824	0.924	0.718	0.819	12.136	12.862	0.642
180	0.833	0.984	0.740	0.831	18.127	11.179	0.249
210	0.832	1.044	0.762	0.841	25.481	8.364	1.113
240	0.844	1.104	0.786	0.850	30.806	6.916	0.735
270	0.867	1.164	0.810	0.858	34.256	6.625	1.027
300	0.862	1.224	0.834	0.865	41.995	3.224	0.366
330	0.873	1.284	0.860	0.872	47.079	1.533	0.167
360	0.860	1.344	0.886	0.877	56.279	3.000	2.020