UNIVERSITY OF NAIROBI

VARIABILITY OF ENGINEERING STRENGTH PROPERTIES OF KENYA PINES

BY

MUKUI A.K.

APRIL 2001

DEPARTMENT OF CIVIL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

VARIABILITY OF ENGINEERING STRENGTH PROPERTIES OF KENYA PINES

BY

MUKUI A.K.

A thesis submitted in part fulfillment for the degree of
Master of Science in Civil Engineering
University of Nairobi

APRIL 2001

DECLARATION

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

Sign ______________________ Date: 10/5/2001

Mukui A.K.

This thesis has been submitted for examination with my approval as University Supervisor.

Sign ______________________ Date: 10.5.2001

Mr. S.S. Miring'u

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF NAIROBI
P.O. BOX 30197
NAIROBI

ACKNOWLEDGEMENTS

It would not have been possible to do a research of this magnitude were it not for the keen supervision by my supervisor, Mr. S.S. Miring’u, of the department of Civil Engineering, University of Nairobi. He worked tirelessly to supervise and to provide the necessary guidance and direction. My heartfelt appreciation also goes to Mrs. Mumenya of the same department for her helpful contribution throughout the project. I am also grateful to other lecturers from the same department who assisted me in one way or another towards the completion of this thesis, and especially to Dr. B.N.K. Njoroge for his trustworthy guidance and support.

My gratitude also goes to the department's laboratory technicians, and especially to Mr. Maina, Mr. Nakhale and Mr. Owuor, of timber laboratory for the assistance they gave in carrying out the laboratory tests.

I am also very grateful to the centre director of Kenya Forest Research Institute, Mr. Githiomi and the other staff, and the staff of Kenya Bureau of Standards for the invaluable help they gave me in terms of information and technical assistance.

I feel highly indebted to my family members and notably Francis Githua, colleagues and everybody else who made any contribution towards the preparation of this thesis.

My special thanks goes to my wife, Beatrice Wanjugu, who stood with me and bore it all when we wedded before the completion of this project.

Above everyone else, I thank God who strengthens me, and in whose ultimate plan I wrote this thesis.

DEDICATION

To my wife Beatrice and to my parents

Your unfaltering love, patience and encouragement were the impetus for the successful completion of this research work.

ABSTRACT

An investigation into the high variability of engineering strength properties of Kenya pine timbers has been carried out. Pine timbers from ten sawmills throughout the country and from the main timber growing regions were sampled and tested for the strength properties.

The theoretical part of the study covered the review of strength testing and results obtained by others (7, 11) and the properties of wood and timber as an engineering material. Various strength properties were studied together with the effects of strength educing defects. Grading standards were also looked at.

The following engineering strength properties of timber were calculated in accordance with BS 373:

- Bending parallel to grains
- Compression parallel to grains
- Tension parallel to grains
- Shear parallel to grains
- Modulus of elasticity

The raw data was used to obtain two other sets of data, one through data trimming and the other through logarithmic data transformation. Each set of data was then statistically analysed. The logarithmic transformation yielded the best results and led to increase in the derived basic stresses for the timber.

Identification of compression wood proved difficult and though the variability is chiefly as a result of this wood, adequate measures to identify it or deal with its effect on strength were not addressed.

SYMBOLS

N = Number of tests

X_i = i^{th} test value

l = Length of class interval used to draw histogram

σ = Standard deviation of test results

μ = Mean of test results

f_{min} = Statistically estimated minimum strength

f_b = Basic stress

k_r = Reduction factor

k_d = Depth modification factor

k_p = Probability coefficient

e = 2.7183 (a constant)

π = 3.1416 (a constant)

P' = Load at proportional limit (N)

P = Ultimate load (N)

L = Length of beam between supports (mm)

r = Correlation coefficient

d = Density (g/cm^3)

ACRONYMS

GS	General structural
SS	Special structural
MGS	Machine general structural
MSS	Machine special structural
MOPW	Ministry of Public Works and Housing
KEFRI	Kenya Forest Research Institute
KEBS	Kenya Bureau of Standards
BS	British Standard
KS	Kenya Standard
LCL	Lower confidence limit test value
KAR	Knot area ratio
ASTM	American Society for Testing and Materials
MOR	Modulus of rupture
MOE	Modulus of elasticity, also designated as **E**
LOP	Limit of proportionality
MC	Moisture content
Comp	Compression
CV	Coefficient of variation
Eq.	Equation

CONTENTS

CHAPTER 1

CHAPTER 2

Contents continued...

CHAPTER 3

CHAPTER 4

CHAPTER 5

APPENDIX

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.0 KENYA PINES AS COMMERCIAL TIMBER

The main source of commercial timbers in Kenya is softwood forest plantations. These plantations are generally found in a narrow band on either side of the equator extending westwards from Mt. Kenya to Lake Victoria. Very little if any softwood plantations exist on the east of Mt. Kenya and in the extreme north or south of the country. The total volume of lumber estimated at 200,000 m^3 per year is made up of cypress (45%), pine (31%), eucalyptus (10%) and others such as cedar, podo and hardwoods (14%)[15].

Although the leading type of commercial timber is cypress, pine that comes second has certain advantages over cypress in that it has a higher resistance to pests and diseases and it seeds early to support faster expansion of plantations. As a construction timber however, pine has some disadvantages in that it has a higher occurrence of sloping or twisted grains, it may contain resin stains and its derived stresses for use in engineering design are relatively low compared to cypress. In the near future, pine is likely to take the position of cypress as the leading commercial timber in Kenya owing to a recent aphid attack on cypress where many acres of forest plantations under cypress were destroyed.

Although usually regarded as one type of timber, pine is a botanical family of trees consisting of a vast number of species growing in different regions of the world. Pines belong to a class of trees called *conifers* which are generally cone bearing with needle-like or scale-like leaves, but some conifers such as larches are deciduous. Pines are particularly distinguished for their needle-like leaves. Conifers, together with other trees such as ginkos and cyads that bear rather unprotected seeds, are collectively called Gymnosperms and produce softwoods. On the other hand, broad-leaved tree species belong to Angiosperms and produce hardwoods. The terms 'softwood' and 'hardwood' do not necessarily refer to the relative hardness of wood as some softwoods are harder than some hardwoods.

There are two major species of pine grown in Kenya namely *Pinus patula* and *Pinus radiata*. Pinus patula was introduced into the country after Pinus radiata that had been introduced earlier suffered a damaging fungal attack. Presently, large amounts of both timber species are available in the market making pines a major type of construction timber in Kenya. It is difficult to distinguish visually between these two in the converted form and they are thus treated as one type of timber for all practical purposes.

1.1 PROBLEM STATEMENT

Being a natural material, timber exhibits a relatively higher variability in terms of engineering strength properties compared to other materials such as concrete and steel. This variability is exhibited in high coefficients of variation for test results on the strength properties and it is higher for tropical than for temperate timbers[14]. However. Kenya pines have been found to have exceptionally high variability even when compared to other tropical timbers, as seen in the comparison with Kenya cypress in table 1.1. The values in this table were obtained from a research report of MOPW by Harley[11], from which the following other conclusions were made.

i) For all strength properties except shear. the average strength values for pine are higher than those for cypress.

ii) The coefficients of variations are much higher for pine than for cypress.

iii) Although pine has higher average strength values than cypress, the derived grade stresses are much lower for pine than for cypress.

iv) It may be inappropriate to derive the grade stresses for Kenya pines using the method adopted for other timbers.

Table 1.1 Comparison between Kenya pine and cypress (stresses in N/mm²)

Stress Type	Stress Parameter		Pine	Cypress
Bending parallel to grain	Average		81.852	69.300
	Basic		9.0	15.1
	1% lower confidence limit		22.373	37.827
	Coefficient of variation		31.187	19.492
	Grade stress:	GS	3.0	5.0
		SS	4.3	7.1
Compression parallel to grain	Average		42.415	37.820
	Basic		7.9	13.6
	1% lower confidence limit		11.035	19.011
	Coefficient of variation		31.752	21.345
	Grade stress:	GS	3.6	6.0
		SS	4.3	7.0
Shear parallel to grain	Average		12.15	12.29
	Basic		1.9	2.5
	1% lower confidence limit		5.9	7.67
	Coefficient of variation		22.03	16.11
	Grade stress:	GS	0.9	1.1
		SS	0.9	1.1
Modulus of elasticity	Average		11081	8133
	Basic		4290	4000
	5% lower confidence limit		3660	3268
	Coefficient of variation		38.6	31.3
	Grade stress:	GS	3900	3600
		SS	4300	4000

Grade stresses are the stress values actually used in timber engineering design for a specific species and grade of timber when all the factors that affect its structural performance have been considered.

Campbell[7] made the following provisional findings on the variability of Kenya pines:

(a) The ratio of maximum to minimum strength was of the order of five

(b) 60% of the samples were twice as strong as the 1% LCL

(c) 23% of the samples were three times stronger than the 1% LCL.

(d) 7% of the samples were over four times stronger than the 1% LCL

(e) Pinus patula was slightly stronger than Pinus radiata but the difference was not significantly large

(f) There was a high proportion of compression wood in the Kenya pines

(g) The assumption of normal distribution of test results appeared invalid as a positive skew was noted

(h) It may be difficult to machine-grade Kenya pines due to their high variability

(i) Variability between mature and immature pine was noted. However, it would be impractical to derive separate grade stresses for mature and immature pines

Variability in timber strength properties exists within a tree, between trees and between sites. Patterson[19] made the following observations on Kenya pines:

- Within a tree, strength increases from the pith outwards. It also increases with density, latewood content and fibre length while it decreases with increasing width of the growth rings.
- The variability between trees is very large and warrants statistical consideration in derivation of grade stresses
- Little variability was observed between sites but this presented no statistical justification that pines from different sites have different strength properties
- The standard method of selecting samples uniformly across a log section is not appropriate for Kenya pines as it gives undue weight to the weaker inner core

For practical purposes however, it is only the variability between trees rather than within a tree or between sites that can be effectively analysed in the derivation of appropriate grade stresses for Kenya pines and for any other timber.

The grade stresses reported for Kenya pines are quite low relative to those obtained for pines from other regions of the world. However the other pines compare well among themselves as seen in the table 1.2 below. Values for Kenya pines are from Harley[11] while those for other pines are from BS 5268: 1996.

Table 1.2 Grade stresses for pine timbers from different regions (N/mm^2)

Grade stress		**Kenya pine Kenya**	**Corsican pine British**	**Parana pine S America**	**Pitch pine Caribbean**	**Southern pine U.S.A.**
Bending parallel	SS	4.3	6.8	9.0	10.5	9.6
to grains:	GS	3.0	4.7	6.4	7.4	6.8
Shear parallel to	SS	0.9	0.82	1.03	1.16	0.98
grains:	GS	0.9	0.82	1.03	1.16	0.98
Comp. parallel	SS	4.3	7.5	9.5	11.0	10.2
to grains:	GS	3.6	6.1	8.1	9.4	8.7
Modulus of	SS	4300	7000	7500	9000	8500
elasticity (min)	GS	3900	6000	6000	7500	7000

From the above observations, it is evident that there may be considerable wastage of unidentifiable strong timber whenever Kenya pines are put to structural use since the grade stresses used in design are very low. The standard method of deriving grade stresses from test results does not consider such high variability as in Kenya pines and this has resulted in the low values. It therefore seems inappropriate to apply these methods directly on Kenya pines as applied on other timbers.

If the wastage is to be minimised and better utilisation achieved, more appropriate grade stresses for these timbers must be sought. This can be achieved by revising the statistical treatment of test results or by revisiting the grading process for Kenya pines to incorporate the causes of the high variability. This calls for more research on the variability of these pines as mentioned by both Patterson and Harley.

1.2 RESEARCH OBJECTIVES

The grade stresses for Kenya pines are very low due to wide scatter of test results and the wrong assumption that they are normally distributed. Provisional results found the distribution to have a positive skew and an exceptionally large scatter. The 1% lower confidence limit values are not appropriate and neither are the derived grade stresses. Test results on cypress indicate that the assumption of normal distribution is appropriate (though not strictly true) and the scatter compares well to other tested timbers, thus the stated problem of Kenya pines is unique. The main objectives of this research are:

(i) To establish the engineering strength properties of Kenya pines in view of the high variability

(ii) To establish the cause of high variability of these properties.

(iii) To establish a suitable statistical method of data analysis and calculate grade stresses.

With more economic and better utilisation, pine is likely to take the place of cypress as Kenya's leading construction timber, owing to a recent damaging aphid attack on cypress.

1.3 RESEARCH METHODOLOGY

This research is based on extensive laboratory tests to establish the bending, compression and shear behaviour of Kenya pine timbers. As these timbers have been observed to exhibit an exceptionally high variability in engineering strength, the test results will be subjected to appropriate data analyses, which include data trimming and data transformation. These alternative analysis procedures were arrived at, with the knowledge that the standard practice in timber engineering is to assume normal distribution of strength test results. The relevant statistical tools have been used in the data analysis.

1.4 SCOPE OF STUDY

In this study, only Kenya pines have been sampled for the determination of bending, compression and shear behaviour. From the bending tests, the tensile strength and modulus of elasticity have also been determined. For each strength test, the density of specimen and the moisture content at time of test have been determined. The discussion, conclusions and further recommendations are based on the result findings.

1.5 THESIS LAYOUT

The thesis is presented in five chapters. Chapter 1 comprises the introduction, which to Kenya pines as a commercial timber and a statement of the problem of unexceptionally high variability of its engineering strength properties.

Chapter 2, the literature review is in four parts. The first part is a general overview of wood as a resource, its properties and its use as an engineering material. Part two covers the underlying principles and the conventional methods of derivation of timber grade stresses. Part three looks into the timber grading methods while part four has dealt with the timber industry in Kenya.

Chapter 3 is the description of the standard test procedures as carried out in this research.

Chapter 4 comprises the test results, analysis and discussion. Two alternative methods have been advanced as suitable solutions, one through trimming of extreme upper values and the other through logarithmic data transformation.

Chapter 5 comprises the conclusions and further recommendations.

The tables for test result, charts and other relevant information are included in the appendix.

CHAPTER 2

LITERATURE REVIEW

2.1 WOOD AS AN ENGINEERING MATERIAL

2.1.0 GENERAL

The use of wood for construction dates back to early civilisation, yet it remains a primary building material to-date. The industrial revolution of the earlier centuries was quickened if not facilitated by the availability of wood that was then used for making machine parts, industrial structures and for fuel. Despite the high competition from other building materials, many industries still depend on wood for their construction requirements. Such industries are the transport, communication, building, mining, agricultural and navigation industries, among others. Timber is used extensively all over the world for construction of domestic and institutional houses and structures, as well as framing and roofing trusses for many structures

A prerequisite to rational utilisation of timber and of any other material is a sound knowledge of its properties and its performance in service with an understanding of its advantages and disadvantages over other alternative materials. Such knowledge is important for the improvement of quality of timber produced in the forests and for optimal use of the available species.

Certain advantages listed below have made wood remain a favoured construction material over the years:

- Timber has a high strength to weight ratio, superior to concrete and steel.
- It can be shaped and machined easily with low consumption of energy.
- Jointing in wood is easily achieved using simple fastening devices and tools.
- It has low heat conductivity and insulates electricity.

- It has good acoustic properties
- It does not oxidise and has considerable resistance to mild concentrations of acids
- It exhibits little thermal contraction and expansion.
- It is found in most parts of the world at relatively low prices
- It is a renewable resource.

As a construction material, wood also has some disadvantages that make it necessary to make special considerations when using it for construction. These disadvantages are:

i) Being a hygroscopic material, it absorbs moisture when in contact with water or water vapour resulting in strength reduction and dimensional changes
ii) It is an anisotrophic material i.e. it exhibits different mechanical properties in different directions.
iii) It may burn and decay.
iv) Being a product of biological processes, it has variable structure and properties depending on the species, age, heredity and growth conditions.

The quality of timber produced from the parent tree is a primary aspect in timber engineering. This quality can be improved within limits through selection and propagation of genetically superior breeds and controlled harvesting. Other measures that can be used to improve the timber quality in forests are pruning and spacing of trees. The trees in the forests should also be protected from strong winds, disease causing microorganisms and other adverse effects.

Effects of the disadvantages of timber can be controlled in various ways. The problem of hygroscopicity can be overcome for practical purposes by proper drying or treatment of wood to avoid the associated undesirable effects of checking, warping, twisting and cupping. Mechanical anisotropy is advantageous in certain types of loading such as axial loading. However, it may be mitigated in wood-based materials such as plywood, particleboard, block board, etc. Wood may be protected from fire using fire retardant chemicals. Its resistance to insects, fungi and other destructive agents can be greatly increased by use of chemicals to improve its durability. Timber is variable in anatomical structure and properties between trees in a species and across different species, but such variability may not cause problems if it is taken into consideration when the timber is put into its end use.

In summary, though timber has some disadvantages as a construction material, good control can ensure proper utilisation of this precious natural resource.

2.1.1 ENVIRONMENTAL IMPACT OF WOOD UTILIZATION

With the growing global concern on environmental conservation, it would be incomplete to talk about the proper utilisation of any natural material without assessing the environmental implications of its exploitation. In this assessment, wood has been considered as a resource not only for the construction industry but also as a raw material for a large number of products. The products of primary industrial processing includes poles, posts, timber, laminated timber, veneer, plywood, particle board, fibreboard, pulp and paper. Wood products from chemical processing include synthetic fibres, photographic films, and explosives. Wood is also used extensively as fuel with about half of the world's wood production being used for either cooking or heating or for steam production.

Of great environmental, scientific and economic concern is the fact that large amounts of harvested wood goes to waste. It is estimated that only a third of the volume produced by trees is finally utilised, the bulk of the waste (30-50%) being in form of residues left out in conversion of logs in sawmills, veneer factories and other logging processes. There are some manufacturing processes that utilise other parts of the biomass produced by trees such as the bark, roots, branches and foliage.

For a product with such multiple utilization as wood, there is usually a danger of overexploitation, with serious negative environmental implications. Unchecked exploitation of wood would lead to desertification with all its associated problems. However, developments and improvements in the efficiency of end uses of wood on one hand should not be seen as incompatible with the desire to conserve forests on the other hand. Indeed, in areas where wood as a natural resource is well appreciated, appropriate forest management and marketing strategies are given the importance they deserve. The aims of conservation of forests and reforestation are boosted rather than hindered by better utilization of the forests legitimately felled.

Today, wood is a major focus of scientific and technological interest with the aim of acquiring a better knowledge of its structure and properties so as to improve the efficiency of use of its end products. A lot of progress has been made in this area but much more needs to be done to meet the increased demand for wood production and optimal utilisation.

2.1.2 PROPERTIES OF WOOD

2.1.2-1 Cross-section of Wood

The cross-section of a stem is normally circular with three easily identifiable parts namely the pith, the wood and the bark. In between the wood and the bark is a microscopic tissue called the cambium, which produces the wood and the bark.

Pith is normally at the centre of the stem and it may vary in size from a small dot to large and conspicuous size depending on the species. Pith may also vary in colour from whitish to black, and in structure from solid to hollow.

Wood is characterised by the presence of concentric layers known as growth rings, also called annular rings. The pattern of growth rings is due to the mechanism of tree growth whereby one wood layer (and one bark layer) is added during every growth season. Growth rings are more distinct in temperate than in tropical tree species.

In most species, growth rings are easily distinguished from one another because of differences between *earlywood* and *latewood*. Earlywood tissues are deposited during spring while latewood tissues are deposited during summer. These two types of tissues may differ in density, colour and other structural features. In softwood, latewood is darker in colour and has higher density than earlywood. In hardwoods, structural differences are more pronounced.

The number of growth rings on a cross-section near the ground may be used to find the age of a tree. The correct determination of the age of a tree should account for the time taken to reach the height at which growth rings are counted and the presence of false rings.

In many species the inner portion of the stem cross-section is darker than the peripheral. These portions are known as heartwood and the sapwood respectively. As the diameter of the main stem (and of the branches and roots) increases with growth, the older growth rings stop participating in the life processes of the tree but only provide mechanical support, this way forming heartwood from sapwood. This functional change is associated with physiological, structural and chemical changes. Heartwood starts to form in older growth rings near the pith and thus its diameter decreases from the bottom of the tree upward. The relative amount of heartwood and sapwood within a tree differs according to species, age and growth conditions

A common feature of certain softwood is the presence of resin canals, which appear as dark or whitish dots to the naked eye or using a hand lens. The respective features in hardwoods are gum canals.

All wood possesses rays, which appear on a cross-section as lines extending in the general direction from pith to bark. All rays do not however start at the pith but may start within any growth ring. The rays are conspicuous in the some species but hard to distinguish in others.

The bark, which surrounds the central cylinder, differs in appearance according to species and age of a tree. Growth layers in the bark are not distinct but in older trees, two portions of bark may be recognised i.e. inner bark and outer bark. The inner bark is lighter in colour, narrow and moist while the outer bark is dark, dry and corky. The outer layers of the inner bark are gradually changing into outer bark while outer layers of the outer bark are gradually falling off. The external appearance of outer bark as seen on standing trees and logs is usually a characteristic of the species.

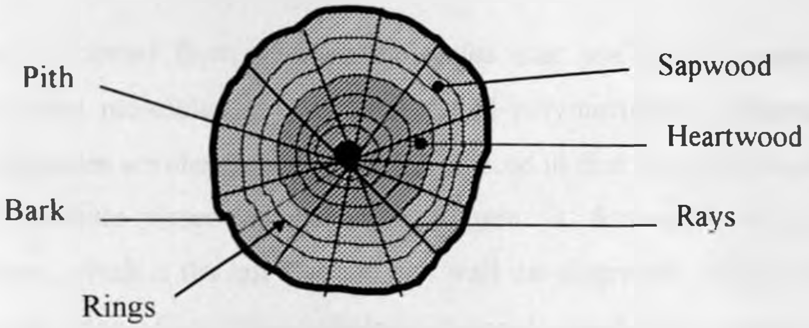

Figure 2.1 Schematic diagram of the wood cross-section.

2.1.2-2 Chemical Properties of Wood

2.1.2-2(a) General

The elementary composition of wood does not differ significantly among the woods, with the principal chemical elements being carbon, hydrogen, oxygen and nitrogen. As a percentage of the oven dry weight of wood, the proportion of these elements has been found to be as follows[23]: -

• Carbon-	49-50%
• Hydrogen	6%
• Oxygen	44-45%
• Nitrogen	1%

Small amounts of mineral elements are also present, the principal ones being calcium, potassium and magnesium, all found in wood ash. The ash content ranges between 0.2 to 1% of the over dry weight of wood.

The principal organic components of wood are cellulose, hemicellulose and lignin.

with small amounts of peptic substances also present. These components are formed by the combination of carbon, oxygen and hydrogen in various chemical forms and proportions. Each of these components includes a number of chemically related compounds that are hard to identify separately.

Cellulose is formed from glucose molecules that are linked together into long cellulose chain molecules, in a process called polymerisation. Hemicellulose and peptic substances are chemically related to glucose in that they are also carbohydrates and carbohydrate-related compounds. Lignin is formed in a process called lignification, which is the last stage in cell wall development. Lignin is the one that differentiates wood from other cellulosic materials produced in nature as it is only produced by living cells. Its composition differs between different tree species.

Other substances that may be included in wood and deposited in the cell lumina and cells walls, but are not part of the wood substance, are called extractives or extraneous materials. Such compounds are gums, fats, resins, sugars, oils, starches, alkaloids and tannins. These substances can be extracted from wood using water or organic solvents and hence the name extractives. Other materials which are regarded as extractives, though not soluble in the above mentioned solvents, are certain organic materials such as calcium salts and ash. This is because they are not cell wall components although they are found dispersed in them.

The smallest structural units of cell walls that may be seen readily with an electron microscope are called microfibrills. Microfibrills are roughly cylindrical and about 10 to 30 micrometers (μm) in diameter, and they aggregate to form macrofibrills. Each microfibrills is a bundle of several cellulose chain molecules that are generally arranged lengthwise relative to the microfibrill axis, but are parallel to each other only in portions called crystalline regions. In these portions the molecules are strongly connected by hydrogen bridges.

2.1.2-2(b) Effects of Chemical Components on Wood Utilization

The chemical properties of wood contribute greatly to its properties and utilisation The high strength of wood in axial tension is primarily derived from the axial arrangement of the cellulose chain molecules. The cellulose framework is bound together and supported by hemicellulose and thus giving the wood the desirable elasticity and compressive strength. Lignin and hemicellulose contribute to the strength of wood in wet conditions significantly. If these two compounds are removed, then the strength of wood in wet conditions reduces to values below 20% of the values pertaining to wood in its natural state while the dry strength increases with the unit area of the remaining tissue[23] In dry conditions, peptic substances and hemicellulose still bond cells to one another but they are unable to perform this function in wet conditions thus reducing the coherence between cells. This explains the difference in strength properties of wood between dry and wet conditions, whereby wood is stronger in the dry conditions and it expands upon gaining moisture.

Wood has high affinity for water and other liquids. This affinity, called hygroscopicity is mainly caused by free OH-groups on cellulose chain molecules. Hygroscopicity of wood is also caused by the presence of hydrophilic substances as peptic substance and hemicellulose. Wood exhibits negligible dimensional changes due to moisture absorption in the axial direction. This anisotrophic characteristic of wood is fundamentally due to the orientation of microfibrills in the cell wall. Most of the microfibrills are arranged parallel to the cell axis and this promotes transverse swelling but which is checked by the almost transverse arrangement of secondary microfibrills. The presence of lignin also affects dimensional stability because it takes up spaces in the cell walls that would be taken up by water. Lignified cell walls shrink less than non-lignified ones.

Wood properties are also greatly affected by the angle of microfibrills. When the microfibrills are parallel to the cell axis, then there is reduced axial shrinkage and swelling and the axial strength is high. The microfibrills angle also affect heat conductivity.

The proportion of crystalline cellulose, or the degree of crystallinity is related to many wood properties such as bending, extensibility, swelling and shrinkage, bonding of fibres, staining, tear and resistance to chemical attack.

Extractives in wood have profound effect on its properties and they are the primary determinants of the differences between species. They influence the colour, odour, taste, fluorescence, durability, inflammability, wood-moisture relations, gluing, pulping and other properties. Woods with toxic extractives have high durability as they resist insect and fungal attacks. Wood-moisture relations such as shrinkage and swelling are dependent on the extraction content of a wood. Wood extractives that have acidic constitution cause wear and corrosion of cutting tools. Certain extractives affect the adhesion of coatings and setting of glues in some manufacturing processes.

The kinds of extractives also influence the chemical reactions in paper and pulp industry, some of which create problems in these industrial processes. The nature of extractives in some woods may result in dust injurious to health during the machining processes. Some of the extractives obtained from wood and bark such as resins and tannins are valuable products themselves. The chemical utilisation of timber is mainly contributed by cellulose, which is used in the manufacture of pulp, paper and a multitude of other products[8,14,23].

2.1.2-3 Mechanical Properties of Wood

The measure of resistance of wood to exterior applied forces defines its mechanical properties. This resistance depends on the magnitude and manner of loading. The exterior applied forces may be in tension, compression, shear or bending. Other loads active in wood may be interior forces due to swelling and shrinkage. Wood has mechanical anisotropy, exhibiting different mechanical properties in different growth directions (axial, radial and tangential).

In wood, as in many other materials, the relationship between stress and strain is linear up to the limit of proportionality, LOP. Above this point, additional stress causes a disproportionately high deformation until the stressed body fails. Below the LOP, a body is elastic i.e it returns to its initial shape and size when the load causing stress is removed. Various mechanical properties of wood are considered below:

2.1.2-3(a) Strength in Tension

Axial tension in wood is much higher (about 50 times) than transverse tension. Single cells (axial tracheids in softwoods) are stronger in axial tension than entire wood while microfibrils are even stronger. Cellulose chains are strongest in axial tension with strength estimated to be 7500N/mm^2 compared with a range of 50 - 160N/mm^2 for wood. The successive reduction of strength from cellulose chains to wood is due to deviations of cellulose chains and microfibrils from parallelism to tree axis, and to presence of low strength chemical substances between cellulose chains, microfibrils and cells.

The axial strength to weight (represented by specific gravity) ratio for wood compares favourably with that of metals and other materials, ranging between 100 - 130N/mm^2 for wood and about 50N/mm^2 for high yield steel. However, the high axial strength of wood is rarely utilised due to development of shear stresses alongside tensile stresses, which are only about 6 - 10% of axial tensile stresses. Axial tensile strength is also greatly reduced by the presence of knots, spiral grain and other growth abnormalities[23].

Transverse tensile stresses in wood are very low and the presence of checks may reduce them to zero therefore their development should be avoided in structures.

2.1.2-3(b) Strength in Compression

Axial compression strength in wood ranges between 25 and 95N/mm^2, being about 15 times higher than transverse compression strength which varies between 1 and 20N/mm^2. Compression strength in wood is mainly contributed to by hemicelluloses and lignin and by cellulose to some extent[23]. Transverse compression strength of wood is important in structures such as railroad ties, timber decking and timber floors, whereas axial compression strength is important in columns. If the slenderness ratio in the latter case is below 11, the strength of column depends entirely on the strength of wood in axial compression, but if greater, the stiffness to resist bucking is important[21].

2.1.2-3(c) Strength in Shear

Shear stresses in a wooden member may be in the transverse plane or in the longitudinal plane when the member is stressed in bending. Axial shear strength of wood ranges between 5 and 20N/mm^2. Transverse shear acting on a cross-section is about 3 - 4 times higher than axial shear but since wood always fails first in axial or rolling shear, transverse shear strength is of no practical importance.

Loads acting at an angle on the transverse plane may cause 'rolling' of fibres in an axial plane producing rolling shear stresses. Oblique shear stresses may occur due to axial tension or compression loads that form oblique shear planes in the cell walls and between cells at an angle of about 60° - 70° relative to the axis of the stressed member. Under the influence of shearing loads, wood fails first in axial shear and thus this kind of shear stress has the greatest practical significance[3].

2.1.2-3(d) Strength in Bending

Bending stresses develop in a member when external forces are applied transversely to the axis of the member. Many members in most wooden structures are loaded in this manner and therefore the strength of wood in static bending is an important mechanical property. In the case of a simple beam under the action of bending forces, three stresses, namely; axial tension, axial compression and axial shear develop. Axial tension and axial compression stresses are highest in the lower and upper surfaces of the beam respectively, diminishing to zero in the neutral plane. Inversely, shear stresses are highest in the neutral plane and zero at the surfaces. The manner of loading whether centre, third-point or uniform determines the distribution of these stresses along the beam[23].

The strength of wood in bending is expressed by the modulus of rupture (MOR), which is the equivalent fibre stress in bending at the time of failure, calculated on the assumption that the usual elastic bending theory applies to failure for a timber-bending member. MOR shows the highest stresses in the outermost fibres of wood when the beam breaks under the influence of a load applied gradually for a few minutes, and it varies between 55 and 160N/mm^2 and is almost similar to strength in axial tension[23].

2.1.2-3(e) Modulus of Elasticity

Modulus of elasticity is used in engineering calculations for estimating the deflection of a bending member, and in calculations for buckling of columns. The values of modulus of elasticity in axial direction vary between 2500 and 17000N/mm^2. Wood has a lower modulus of elasticity than other materials such as steel and concrete and this implies that it bends more under a certain load. The ratio of the modulus of elasticity to weight however compares favourably with other materials. The modulus of elasticity in the transverse direction varies between 300 - 600N/mm^2. Modulus of elasticity is determined from static or dynamic bending tests, but may also be determined from axial tension and axial compression tests. The most accurate way of determining the modulus of elasticity is from axial tension tests but this testing presents practical difficulties in gripping of test samples and is not normally used[1,23]. The modulus of elasticity is calculated from bending tests.

2.1.2-2(f) Cleavage, Toughness and Hardness

Cleavage is a measure of the resistance of wood to external forces acting in the form of a wedge tending to split it. Axial cleavage of wood is low and this is a disadvantage in that wooden members may split when nailed or screwed.

Toughness is the measure of resistance of wood to sudden loading in contrast to the previous cases where loads are either static or slowly applied. Toughness is important in certain wood uses such as tool handles, sports items, boxes and crates. Toughness is an indication of the energy absorbed by wood in dynamic bending.

Hardness is the measure of resistance of wood to entrance by foreign bodies in its mass, and it is higher in the axial than in the transverse direction. Hardness is related to the strength of wood against abrasion and scratching with various objects, and to the difficulty or ease of working wood with tools and machines. Hardness is important for various uses, such as floors, furniture and sports items. Wood ranges from very soft to very hard species[14].

2.1.3 ABNORMALITIES IN WOOD

In the normal process of growth, trees are subjected to various influences throughout their life span, which cause deviations of the wood structure from normal. When such abnormalities affect the service value of wood, they are referred to as defects. Certain normal characteristics of wood such as knots and the pith are also classified as defects since they adversely affect the strength. Mere abnormalities that do not adversely affect strength cannot be classified as defects unless they are pronounced. A feature may also be classified as a defect or not depending on the intended end use of wood. Defects for one end use may be advantageous for another end use. Growth abnormalities in wood greatly contribute to its variability in strength properties from tree to tree within the same species. The common growth abnormalities in wood are

(i) Deviations from typical wood form.
(ii) Spiral grain, knots and other grain deviations.
(iii) Abnormal arrangement of growth rings.
(iv) Disruption of inner wood tissues (compression failures, shakes, resin pockets).
(v) Abnormal colour.
(vi) Wounded wood.
(vii) Abnormalities due to environmental pollution and atomic reactions.
(viii) Reaction wood.

2.1.3-1 Deviation from Typical Wood Form

Typically the tree stem from which wood is obtained is straight and cylindrical with a circular cross-section. Deviation from straightness occurs as a result of leaning, bending, crook, forking and formation of pistol-butted stems. Various environmental factors are involved, some which act mechanically (wind, snow, soil movements), some physiologically (light), and others through destruction by frost, drought, people animals, insects and fungi. Deviation from cylindrical form occurs in the natural taper of stems upwards or due to butt-swell and this becomes a defect only if pronounced. As taper reduces with age, it is advantageous to harvest only mature trees. Butt-swell is a basal enlargement of tree trunk caused by the action of wind on a large crown or a moist site. A tree trunk may acquire a non-circular cross-section either due to hereditary traits resulting in wavy cross-section or due to environmental factors resulting in elongated cross-section.

Pronounced deviations from the typical form lead to high processing waste and produce grain deviations that affect the dimensional stability and strength of timber and other wood products.

2.1.3-2 Spiral Grain, Knots and other Grain Deviations

Spiral grains are formed when wood cells develop in a spiral manner relative to stem axis. The angle of deviation between fibres and stem axis in spiral grains may vary from a few degrees to 90° with variations from pith to bark, from top to bottom and from stem to branches. Spiral grains could be genetic or due to causal factors such as wind action, unfavourable sites and uneven crown development. Earth rotation and solar movements have also been suggested as possible causes[23].

Spiral grain is a serious defect in wood as it reduces the strength considerably depending on the type of loading and the angle of deviation. Closely related to spiral grains are diagonal grains, a defect that arises by sawing or machining straight grained logs at an angle to the growth rings. This usually happens in strongly tapered trees and in trees with irregular circumference or eccentric growth. Since it is hard to find trees with absolutely straight grains, the practice in timber engineering is to limit the grain angle to an acceptable limit.

A special form of grain deviation is caused by the presence of knots. A knot in converted timber is the portion of a branch enclosed in the wood by the natural growth of the tree. While knots cannot be strictly regarded as growth abnormalities, their presence causes grain deviations and discontinuities, voids and stress concentrations in wood.

2.1.3-3 Abnormal Arrangement of Growth Rings

Common deviations from the normal arrangement of growth rings include eccentric location of the pith, false rings, discontinuous rings, indented rings and double or multiple pith formation.

Eccentricity may be caused by one-sided development of the crown that results in better nutrition of one side, deviation of stem from its vertical position or production of reaction wood.

False rings form when more than one growth ring is laid down during a single growing season. This may happen if growth conditions becomes exceptionally good after growth for the season had stopped, making growth to resume.

Discontinuous rings do not circulate fully round the pith and are due to cambium injury or inactivity of cambia resulting from lack of nutrition. False and discontinuous rings cannot be classified as defects as they are not known to cause any adverse effect on the strength. However they may lead to a wrong estimation of the age and growth potential of trees in forest management.

Indented rings result from an abnormal morphology and arrangement of tracheids and rays but they do not constitute a defect as they cause very little grain deviation.

Double or multiple pith formation may result from inclusion of a branch within the stem or combined growth of two or more closely spaced seedlings or sprouts.

2.1.3-4 Reaction Wood

When a growing tree is subjected to stimuli that causes leaning, it develops specialised type of wood called reaction wood to counteract the effects of the stimuli. In softwoods, reaction wood forms on the leeward side of the leaning stem in compression and is called *compression wood*. In hardwoods, reaction wood forms on the windward side in tension and is called *tension wood*. Reaction wood causes eccentricity of growth rings whereby it is contained in the side of stem with wider growth rings and appearing as crescents.

Compression wood differs from normal wood in the following ways;

i) It is darker than normal wood with a reddish-brown colour but it is difficult to distinguish in mild occurrence.

ii) Compression wood tracheids are shorter, have abnormal tips, and are circular in cross-section, leaving large intercellular spaces unlike normal wood tracheids that are closely packed together.

iii) Cell walls in compression wood are thicker and have checks that are not there in normal wood cell walls.

iv) Compression wood contains more lignin and less cellulose than normal wood.

v) With respect to physical and mechanical properties, compression wood has higher density, higher longitudinal shrinkage and higher erratic strength than normal wood. Radial and tangential shrinkage of compression wood is about half that of normal wood.

vi) Regarding the strength to weight ratio, compression wood has been found to be weaker than normal wood, although differences exist depending on the type of loading. Compression wood has relatively low stiffness (MOE), bending strength and toughness, and high shear and compressive strength.

vii) Compression wood breaks with a characteristic brush failure, unlike normal wood.

viii) In normal wood, most strength properties increase with density and with decrease in moisture content below the fibre saturation point. These relationships do not hold for compression wood.

Compression wood is considered as a defect since it can have an adverse effect on timber strength. Its abnormal shrinkage characteristics may lead to checking, warping and other deformations. Sudden failure of wooden members may be associated with compression wood presence. It also affects the chemical utilisation of wood as it yields less cellulose and makes lower quality pulp.

Tension wood, like compression wood appears in crescents but it may also appear in irregular patches. It contrasts compression wood in many respects except that it is also denser than normal wood. In strength, it could be weaker, comparable or stronger than normal wood depending on the type of loading. The normal relationships of strength to density and to moisture content do not apply in tension wood. Due to its erratic strength, tension wood is considered as a defect in structural timber. Its presence makes it difficult to work timber and leaves 'woolly' surfaces on longitudinal sections. It causes warping, corrugation and checks in veneer, among other disadvantages to wood utilisation.

2.2 STRESS DERIVATION

2.2.0 GENERAL

The following discussion on the derivation of grade stresses in timber is in relation to CP112, British Code of Practice for Structural Use of Timber, upon which the grade stresses for Kenya grown cypress and pines were derived. CP112 has since been replaced by BS 5268 and the revisions in BS 5268 have also been discussed here. A Kenyan code of practice for structural use of timber is being developed along the lines of BS 5268. CP112 makes reference to *basic stress*, a term which was not retained in BS 5268, but which continues to play an important part in stress derivation since a wide range of timbers have not been mass tested to BS 5268 specifications. Basic stress continues to provide a basis for design of glue-laminated timber.

2.2.1 BASIC STRESS DERIVATION

Basic stress is defined as the stress that can safely be permanently sustained by timber containing no strength reducing characteristics. The strength reducing characteristics are the defects inevitably contained in timber as sawn from the logs in structural sizes. Such defects include the knots, slope of grains and fissures.

In design, it would be inappropriate to use the basic stress without accounting for the defects allowed in the grade of timber to be used. The established method of deriving basic stresses is based on a statistical analysis of test results on small specimens of timber free from all defects, known as small clear specimens. The methods of test and sampling for such specimens are internationally standardised and are covered in BS 373 and in other codes such as D143-52 of U.S.A. The common standard set of specimens is 20 x 20 mm in cross-section. This small size of specimen has the advantage of enabling sampling from small trees and boards for comparative treatment

Strength reducing characteristics are commonly referred to as defects and were accounted for in practical design by modifying the basic stresses with reduction factors which were related to the maximum size of defects permitted within the grade and to the exposure conditions. This modification was used in design to obtain grade stresses from basic stresses.

In latter work on structural timber, testing samples of graded timber in full structural sizes[14] has derived grade stresses more directly. The essence of using graded timber samples is that they contain defects representative of the grade. This method has shown that some of the earlier assumptions made in derivation of grade stresses from basic stresses were conservative. In particular, it has shown that a relatively high density counteracts the strength reducing defects for a particular grade. This explains why some size of defects for a particular grade could be accepted by machine grading method which is influenced by density while they are rejected by visual grading which is not influenced by density. Testing of full size samples is however an expensive process and is only viable for structural timber of great economical importance and where it is necessary so as to obtain data to derive settings for the mechanical grading of timber.

In the derivation of basic stresses from test results on small clear specimens, account had to be taken of the various factors encountered in service, which affect the strength derived. These factors are:

1. Moisture content
2. Duration of loading
3. Size and shape of members
4. Factor of safety
5. Variability of strength

2.2.1-1 Moisture Content

Moisture content is the amount of moisture in timber expressed as a percentage of the dry weight of its wood substance. The moisture content influences the weight of a piece of timber, its strength properties and propensity to shrink and its susceptibility to attack by insects and fungi. Moisture in living wood cells is present in two forms, either as chemically bound in the cell walls or as free water filling the cell cavities. Upon drying, wood first loses the free water in the cell cavities with little effect on its properties except the weight. On further drying, the cell wall content is affected with significant influence on the wood properties. As wood loses moisture, the hypothetical point at which the cavities are empty while the cell walls are saturated is know as the fibre saturation point. For most timbers, this point is at moisture content between 25 and 30%[14]. If drying continues below the fibre saturation point, the wood begins to increase in strength, stiffness and hardness and in all its mechanical properties and it also starts to shrink.

Since timber is a hygroscopic material, its moisture content is related to the temperature and humidity of the surroundings. It is at only one specific moisture content that a timber will neither absorb nor lose water to the surroundings for any given combination of air temperature and relative humidity. This moisture content is known as the equilibrium moisture content, and is obtained ignoring seasonal differences and considering that the timber is protected only against pockets or pools of water. For the climatic conditions of Kenya the equilibrium moisture content is taken to range between 13% and 15%.

When timber contains moisture in its cell cavities and intercellular spaces which is held by capillary forces only, it is said to be green. Since most of the structural timber readily available from sawmills is unseasoned and is used in exposure conditions of high moisture (say 20-25%), then the strength properties used to compute basic stresses are those of green timber with moisture content above the fibre saturation point. The stresses thus obtained are the green basic stresses and are considered as an estimate of the minimum strength values likely to be achieved in practice.

Timbers with moisture content above the fibre saturation point are allotted the green stresses similar to completely wet wood. However higher stresses are permitted, but with certain limitations, when it is known that the structural member will remain in a dry condition. The basic stresses for dry timber are found by multiplying the green basic stresses by a factor proportional to the ratio of ultimate stresses at equilibrium moisture content and stresses at green condition. This ratio is found from moisture content/strength relationships for the property and species.

Strength values based on different moisture contents may be adjusted to equilibrium moisture content basis for comparison using the following empirical relationship, which was developed by ASTM[14].

$$\log P_e = \log P_f + \left[\frac{M_f - M_e}{M_f - M}\right] \times \log \frac{P}{P_f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq\ 2.1$$

Where:

P = Strength in dry condition i.e. at moisture content below equilibrium moisture content.

P_e = Strength at equilibrium moisture content

P_f = Strength at fibre saturation point equal to green stress

M = Moisture content at which dry test is conducted

M_e = Equilibrium moisture content

M_f = Fibre saturation point.

Alternatively, empirical coefficients of variation of strength with moisture content as tabulated below may be used[22];

Table 2.1 Effect of +1% change in moisture content on strength properties.

Property	Average reduction in strength (%)
Modulus of rupture	4
Modulus of elasticity	2
Compression parallel to grains	5
Shear parallel to grains	3

2.2.1-2 Duration of Loading

The duration of load influences the magnitude of load required to cause failure. Experimentation has established that the strength of timber decreases as the duration of load increases. In general, the influence of duration of load on wood is dependent upon various factors related to wood such as the species, density and moisture content and to the loading conditions such as the magnitude, duration, rhythm and manner of load. The load may be permanent or periodic, whereby permanent loads cause creep in wood while periodic loads result in fatigue, but in both cases the strength is reduced. Permanent loads can reduce the strength by 50 to 70% of the short-term static test values, while periodic loading can reduce the strength to as low as 25% of static values[23]. However, experimental evidence on the effect of duration of loading is limited and the laboratory test results based on a few hours or minutes of loading give comparative values that are only applicable after correction.

In ascribing basic stress to a timber, it is required to estimate a stress level that can be permanently sustained. It is however not known whether there is a stress level below which, a timber will sustain load indefinitely. A permanently sustained stress level is assumed to pertain to the design life of a timber structure. In American and Australian derivation procedures, this stress level has been worked out empirically as 56% (or 9/16) of the ultimate stress achieved in normal duration laboratory test of about 5 minutes. Several other reviews have confirmed that this stress level can safely be permanently sustained and it was adopted in CP112. An empirical hyperbolic equation representing the trends of the data derived from American tests[25] is of the form:

$$Y = \left(\frac{1084}{X^{0.04635}}\right) + 18.3 \qquad \text{eq. } 2.2$$

Where;

X = duration of stress (seconds)

Y = stress level as percentage of standard test result.

Inserted into this equation, the 56% stress level works out to stress duration of over 200 years. This implies that a member will carry a load indefinitely (over 200 years) provided its stress does not exceed 56% of the ultimate stress achieved in the laboratory test. Other empirical expressions give different duration to the 56% stress level but which are sufficiently long to be termed as permanent.

2.2.1-3 Size and Shape of Members

The apparent strength of a timber bending member decreases as its size increases, unlike in most other construction materials. More precisely, the modulus of rupture of a timber beam reduces as the depth increases.

Several theories have been advanced to explain this effect, but none has proved quite satisfactory. One such theory is the 'support theory' suggested by Newlin and Trayer[23] which argued that the fibres in compression zone of a beam act individually as small columns and the more highly stresses fibres near the edge are supported by those relatively unstressed fibres near the neutral axis. If the depth of the beam is small, the supporting fibres are nearer to the highly stresses fibres and hence greater modulus of rupture in a shallow than in a deep beam[2].

Basic bending stress is applicable to 300mm deep beams and a depth adjustment factor should be applied for other all depths. In most cases however, a depth factor is only applied at depths greater than 300 mm for simplicity, resulting in some conservatism when bending members below 300 mm deep are designed. Since the basic bending stress is derived from tests on 20mm deep specimens, a depth modification factor should be applied to the test results in the derivation.

The depth modification factor k_d is given as the ratio of modulus of rupture of a beam depth d to that of a beam 300mm deep. For a beam of depth greater than 300mm, k_d is given by the expression[6,10]:

$$k_d = 0.81 \times \left(\frac{d^2 + 92300}{d^2 + 56800} \right) \quad \text{......} eq.2.3$$

Based on this expression, the depth factor given in CP112 to modify from 20mm to 300mm deep beam is 0.84. Another adjustment equation by Bohannan^2 worked out an almost similar factor of 0.86. At large depths like in laminated construction, alternative expressions give diverse depth factors. BS 5268 has adopted similar depth factors and has included other factors for depths below 300mm as follows:

For timber beams having a depth of 72mm or less, $k_d = 1.17$.

For timber beams having a depth of greater than 72mm and less than 300mm k_d is given by:

$$k_d = (300/d)^{0.11} \quad \text{......} eq.\ 2.4$$

The above formulae for k_d are limited in that they were derived for clear Douglas fir beams up to 400 mm deep. There is no information on other species, greater depths or effect of defects. However in actual practice it is rare to use solid members over 300mm deep and the design of deep laminated beams is governed by lateral stability considerations. In the absence of more detailed information, this formula is considered sufficient and has been adopted in the codes of practice for timber design.

2.2.1-4 Safety Factor

In every engineering work involving the use of a structural material, it is important to provide for contingencies, which may arise in the design, fabrication and use of the structure. Such contingencies include deliberate or accidental overloading, variations between assumed and actual weight of structural materials, assumptions made during design and design inaccuracies, and variations in quality control. The value given in CP112 for factor of safety is empirical and equal to 1/0.8, adopted from Pearson, Kloot and Boyd[20]. With adequate allowance for duration of load and size effect, a small safety factor would be sufficient.

2.2.1-5 Variability of Strength

Variations in the strength of timber specimens occur within a particular tree, across different trees within a particular species, and across the species. Variability within a particular tree has no practical significance since it would be difficult to control the cutting of timber from specific points of the tree trunk. In timber engineering, each timber species is treated as an independent entity with design strengths given for as many structural species as possible from the testing authorities. It is therefore not necessary to consider the variability of timber across the species in the context of this work.

Of great importance to timber engineering however, are the wide variations that occur in the strength of specimens within a particular species. These variations are caused by factors such as growth conditions, age, heredity and source of the timber. If a small number of test specimens are used, the test results appear to vary erratically but if the number of specimens tested increases, the variability starts to assume a pattern. If the results for a large number of tests are plotted to form a histogram with class intervals as small as possible, then the top of the histogram tends to form a smooth curve. A form of theoretical distribution can be superimposed upon the histogram to fit and then statistical methods related to the fitted distribution can be used in the derivation of the basic stresses. In a well quoted example, 2708 bending tests under central loading point on Baltic redwood were done at Princes Risborough Laboratory to establish the modulus of rapture[1]. A normal (Gaussian) distribution curve superimposed on the histogram gave a sufficiently accurate fit to justify the use of statistical methods related to it to derive the basic modulus of rupture. Experiments have shown that the difference between the actual and theoretical distribution in the above example is typical of other species and strength properties. It is therefore usual to assume a normal distribution of test results in timber engineering. The statistics needed to draw the normal distribution curve are only the arithmetic mean and standard deviation.

Variability is accounted for by considering a statistically estimated minimum stress below which a specimen is not expected to fall according to a chosen level of probability. This stress level is the lower exclusion limit or the lower confidence limit (LCL) shown in the figure below.

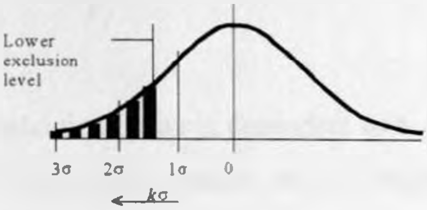

Figure 2.2 Normal distribution curve with lower exclusion limits shown

Where overstress can lead to sudden failure, CP112 takes the lower 1% exclusion limit, which is equivalent to a probability level of 1 in 100. The statistically estimated minimum is thus taken to be the value above which 99% of the results should fall. This probability level applies to bending, tension, shear and compression parallel to grains. Where there is no possibility of sudden failure as in compression perpendicular to grains, a lower probability level of 1 in 40 is taken[3]. Probability levels of 1 in 100 and 1 in 40 have probability coefficients k_p of 2.33 and 1.96 respectively. The statistically estimated minimum strength is obtained from the expression:

$$f_{min} = \mu - k_p \sigma \qquad \textit{eq. } 2.5$$

2.2.2 COMBINED REDUCTION FACTORS

Once the minimum strength is computed from statistical analysis of test results, a reduction factor k_r must be applied to account for the influences of long duration loading, size of member and factor of safety in order to obtain the basic stresses. Sunley[21] suggested that rather than trying to estimate the value of each variable that contributes to the reduction factor, a single reduction factor should be used which would ensure that reasonable basic stresses were obtained for species which had been widely used over a long period of time. The general formula for computing basic stress for each species and strength property is thus:

$$f_b = \frac{\mu - k_p\sigma}{k_r} = \frac{f_{\min}}{k_r} \quad \text{.........} eq.\ 2.6$$

The choice of the single reduction factor is dependent to a great extent on engineering judgement based upon limited information on the behaviour of laboratory test specimens instead of actual structural components, and upon the observed adequacy of design and fabrication methods over the years. Each strength property has its appropriate reduction factor used as a divisor to the statistically estimated minimum strength.

2.2.2-1 Bending and Shear Stresses

A combined reduction factor of 2.65 for tropical timbers and 2.25 for temperate timbers was chosen as a divisor for the statistically estimated minimum strength. A relative lack of familiarity with tropical timbers for researchers who developed these factors led to the choice of a more conservative reduction factor for these timbers. The combined factor of 2.65 may be derived from the reciprocals of individual factors as show below[14]:

$$\gamma_{combined} = \gamma_{duration} \times \gamma_{depth} \times \gamma_{safety} \quad \text{.........} eq.\ 2.7$$

Where $\gamma_{combined}$ = Combined reduction factor equal to 2.65

$\gamma_{duration}$ = Load duration factor equal to 1/0.56

γ_{depth} = Depth factor equal to 1/0.84

γ_{safety} = Safety factor equal to 1/0.80

2.2.2-2 Compression Stresses

The ratio of the limit of proportionality to ultimate stress is higher in direct compression than in bending parallel to grains and there is a lesser size effect for a compression than for a bending member. It is therefore justifiable to take less caution in a compressive member than in a bending member. Sunley suggested a divisor equal to 62 percent of the bending divisor, which works out to 1.6 and 1.4 for tropical and for temperate timbers, respectively. Pearson, Kloot and Boyd gave combined reduction factors of 2.0 and 1.7 for tropical and for temperate timbers, respectively. The 2.0 value comprises of 1/0.56 for duration of load and 1/0.8 safety factor, without a size effect factor since it is not significant in a compression member.

Compression perpendicular to grains is not a critical structural property and the reduction factor taken for this property is 1/0.63 in CP112, although Pearson, Kloot and Boyd suggested a factor of 1/0.75.

2.2.2-3 Modulus of Elasticity

The modulus of elasticity is derived from the linear portion of the load-deflection curve from static bending tests on small clear specimens. If a bending member is to act alone, the statistical minimum modulus of elasticity based on the 1% LCL is required without a divisor. Where four or more members are to act together to support a common load, the mean modulus of elasticity is used. The value for two or three members supporting a common load can be obtained by linear interpolation

In calculations for buckling, more caution is required since an over-estimation of the modulus of elasticity could lead to failure, in addition to excessive deflection. In this case, a reduction factor of 1.5 is applied to the minimum modulus of elasticity value, but this is built in into the expressions for design of compression members rather than being included in the derivation for modulus of elasticity[14].

2.2.2-4 Tension

Tensile strength parallel to grains for clear timber is in the same range as bending strength, but greater than compressive strength. However defects have a more pronounced effect on tensile than on bending or compressive strength. Due to this, the basic tensile stress has been set as 60% of the bending value for all tropical timbers in CP112 and BS 5268.

Table 2.2 below is a summary of the magnitude of the combined reduction factors for tropical timbers and the probability used to determine the minimum for each property in CP112[3] method of derivation.

Table 2.2 Basic Stresses: Probability and reduction factors for derivation

Property	**Probability determining minimum**	**Minimum reduction factor**
Bending	1 in 100	2.65
Compression parallel to the grains	1 in 100	1.70
Compression perpendicular to grains	1 in 40	1.60
Shear parallel to the grains	1 in 100	2.65
Mean modulus of elasticity	_____	1.00
Minimum modulus of elasticity	1 in 100	1.00

2.2.3 BS 5268 REVISED METHOD OF STRESS DERIVATION

As the world tends towards becoming a global village, there has been a move to integrate the codes of practice and standards used in different regions. In line with this, the British Standards Institutions replaced CP112, the British code of practice for the structural use of timber, with a new standard BS 5268. Part 1 one of the new code, titled "Limit State Design" is not yet ready, while Part 2 titled "Permissible Stress Design" is a revision of CP112 which also dealt with permissible stress design in timber.

The limit state design in part 1 is to be based on timber properties computed on the basis of 5% lower confidence limit and the strength values thus given in BS 5268 have been computed on this basis. The probability coefficient k_p for 5% LCL is 1.65. The use of a strength value above which 95% of the results fall, rather than 99%, would result in less continuous design if no further adjustment is made. Consequently, an additional factor of 1/1.18 has been incorporated in derivation of BS 5268 properties to maintain on average the same broad level of material safety.

Other changes incorporated include increasing the modulus of elasticity by 1.2 to reflect higher values found in structural size testing of graded timber compared with small clear specimens. These higher values can be partly attributed to the arrangement of structural size tests, which avoids inclusion of deflection due to shear effects. The values of compression perpendicular to grains for BS 5268 have been computed simply as a fifth of the basic bending stress.

It is only the dry grade stresses that have been tabulated in BS 5268, so as to harmonise with other codes. The green stresses are obtained by further modification factors as given in the code. Below is a summary of the reduction factors adopted for derivation of dry stresses to BS 5268 method[14].

Bending Stress:

• Section depth;	From 20mm to 72mm	0.8547 (1/1.17)
	From 72mm to 300mm	0.8547 ($(72/300)^{0.11}$)
• Duration of load		0.5625 (9/16)
• General safety		0.855
• 5th to 1st percentile		0.8474 (1/1.18)

Product of above factors = 0.2977

⇒ Dry basic bending stress (MOR) = 0.2977 x 5% LCL of test results after adjusting mean test modulus of rupture to equilibrium moisture content.

⇒ Dry basic tensile stress (T) = 0.6 x basic bending stress

⇒ Dry basic compression parallel stress (C)= 5% LCL ÷ 2.45

- ⇒ Dry basic compression perpendicular stress (Cr) = basic bending stress ÷ 5
- ⇒ Dry basic shear parallel to grains stress = 0.729 x 5% LCL ÷ 2.65
- ⇒ Mean modulus of elasticity = 1.2 x mean of test results
- ⇒ Minimum modulus of elasticity = 1.2 x 5% LCL
- ⇒ Modulus of elasticity perpendicular = 0.05 x permissible modulus of elasticity
- ⇒ Tension perpendicular = 1/3 x shear parallel to grains stress
- ⇒ Torsional shear = 1/3 x shear parallel to grains stress
- ⇒ Rolling shear = 1/3 x shear parallel to grains stress
- ⇒ Shear modulus = 0.625 x permissible modulus of elasticity

2.3 STRESS GRADING OF TIMBER

2.3.0 GENERAL

Grading of timber involves the allocation of wood to a class or grade according to the end use to which it is to be put, and as specified by the grading rules being used. Grading rules determine the grades of timber through specifications and controls that limit the allowable size of defects in a specified grade. Defects are natural features of timber, which may be regarded as imperfections as far as the use in question is concerned.

In timber for structural use, the most important defects are the knots, sloping grains and fissures. Other defects of less importance but which should nevertheless be considered are wane, damaged wood, wormholes, stain, fungal decay and other inherent abnormalities. It would be futile to specify timber free from all defects, as this will not only be uneconomical but also unavailable. The aim of grading rules is to define limitations upon these defects such that the timber would not be rendered unsuitable for the purpose for which it is intended.

Timber grading is usually done through visual inspection aided by simple tools but it could also be done with specialised machines. Two basic systems of grading sawn timber have been advanced namely the **cutting system** and the **defect system**. A special form of defect system is **stress grading,** not to be confused with mechanical grading system whereby the effects of defects on strength are considered.

2.3.1 CUTTING SYSTEM

This system is suitable for grading timber that will be resawn to smaller size before use. The grade is determined as the percentage of the total surface of the worst face of a piece that can be included in a specific number of cuttings. A cutting is a rectangular portion of a piece that can be obtained by resawing. The best timber grades obtained from the cutting system of grading yield the highest proportion of clear face cuttings. This system is however not appropriate for structural use.

2.3.2 DEFECT SYSTEM

This is used for grading timber for special purposes where it is used in exact sizes in which it is supplied. For each grade, the permissible defects are defined and any piece containing more defects than allowed is rejected.

A special type of defect system of timber grading is stress grading because of its specific objective. In stress grading, the objective is to grade timber such that each piece of timber of a given size and identity in a given grade will have a certain minimum strength. It is necessary to re-grade stress graded timber if it is resawn or surfaced to an extent beyond certain controlled limits which only allow for normal finishing and dimension fitting processes. Stress grading is the most suitable grading system for structural timber. There are two main methods of stress grading, namely:

1. Visual stress grading
2. Machine stress grading

2.3.2-1 Visual Stress Grading

There are various types of visual grading rules encountered throughout the world, some in which the grades defined are multi-purpose applicable to all structural timbers. Other visual grading rules classify stress grades by size and use groups. Any set of grading rules seeks to limit the size and position of knots, fissures and slope of grain, among other defects. However, it is the method of measurement of knots that gives rise to the various types of visual stress grading rules. One method of measurement of knots depends upon the determination of the diameter of the knots, with additional provision for non-cylindrical knots. Another method of measurement limits the knot area ratio, which is the ratio of the sum of projected cross-sectional area of all knots at a cross-section, to the cross-sectional area of the piece.

The method of measurement of defects and the grade limitations for each defect are contained in BS 4978, the British standard specification for softwood timber grades, and other relevant publications. Two primary visual grades are described as General Structural (GS) and Special Structural (SS). The GS grade is intended to provide a description of the minimum acceptable quality of timber for structural use. On the other hand, the SS grade provides a superior grade, which would be suitable for use in special structures and as principal members. These two grades are such that an ordinary commercial parcel would have a reasonably high yield of both grades.

Stress grading allows for the presence of strength reducing defects in a timber but within limits specified such that the strength does not go below a certain minimum strength for the grade. Grade stresses are thus obtained by multiplying the basic stresses, applicable to ideal structural elements free from all strength reducing defects, by a value known as the strength ratio. There is a specified strength ratio for each strength property and grade, but which is independent of species. Table 2.3-1 gives the grade ratios for BS 4978 GS and SS grades.

Table 2.3 Grade ratios for BS 4978 GS and SS grades

Property	**GS grade**	**SS grade**
Bending	0.35	0.5
Mean modulus of elasticity	0.9	1.00
Compression parallel to grains	0.44	0.63
Shear parallel to the grains	0.54	0.54
Compression perpendicular to grains	0.68	0.76
Tension parallel to grains	0.24	0.35

Tests on graded timber in full structural sizes have lately been used in the determination of strength ratio, whereby the results are compared with the basic stresses for the same timber

2.3.2-2 Machine Stress Grading

In machine stress grading, the more indicative property of timber is measured using a non-destructive testing machine. Earlier, machine graded timber would qualify for general structural use in any structural element, but simple grading machines have recently become available that can grade timber for limited end use such as jointing. The visual timber grades can be graded out by machine, in which case they are described by the abbreviations MGS and MSS. Higher machine stress grades are however permitted.

2.4 USE OF STRUCTURAL TIMBER IN KENYA

2.4.0 GENERAL

The structural timber industry in Kenya is young and not highly developed. The first published guidance on grade stresses for Kenya grown timbers was in 1963 by Patterson[19] followed by several papers by Campbell[7] in the sixties and early seventies It was not until the eighties that the structural department of the Ministry of Public Works[11] undertook extensive strength tests to update the grade stresses for pine and cypress timbers, which form the bulk of structural timbers in Kenya.

In the Kenyan construction industry, timber is generally regarded as a secondary construction material, used only when there are financial constraints or when the structure being built is temporary. However structural timber is used extensively in roofing trusses for homes and institutions, mainly due to the higher cost of alternative materials such as steel The extensive use of timber to construct modern homes and as framing for large important structures such as concert halls, sports and leisure centres has been hindered by several factors as listed below: -

i) Lack of the proper technology and reference information for design and erection of timber structures

ii) Conservatism by many people who regard timber as a traditional material and therefore unacceptable for modern structures.

iii) Lack of proper information on wood preservation has lead to an overestimation of the hazards to structures by fungal and insect attack, leading to higher insurance and mortgage premiums on timber structures.

iv) There is a general feeling that timber structures lack permanence and can only be used on temporary structures

v) Technological development in the use of other construction materials especially concrete and steel has downgraded timber as a suitable alternative

vi) Due to increased deforestation and the need to conserve the forests, the authorities have imposed a control on feeling of trees and thus pushing the timber prices up.

vii) Some cultural customs force the use of a specific building material as opposed to timber, making it unpopular in such areas.

None of the above setbacks to the use of structural timber in Kenya is of a permanent nature and a correct approach to each problem can lead to increased domestic utilisation of structural timber. In order for timber to be appreciated as a competitive construction material for modern structures in the country, there is need to provide the lacking information and technology, together with sensitising the public on the true performance of timber. There is also need for better co-ordination of the timber industry. This way, most people would be able to enjoy the numerous advantages of timber, given that it is a renewable resource found extensively in many parts of the country. If the value of timber as a resource can be fully appreciated, then afforestation, good forest management and better marketing strategies would be adopted even by individuals in their private capacities. This would in turn lead to a rapid growth in the timber industry, as there would be a high demand for good material and quality control and use of appropriate technology.

2.4.1 STRESS DERIVATION IN KENYA

As for most engineering materials, structural use of timber is governed through relevant codes of practice and standards which have been developed through testing and experience over the years. Since timber is a natural and variable material, each code of practice or standard is applicable only to the country or countries for which it was developed. Codes of practice from one region can however be adopted for other regions, but with caution and certain necessary modifications to account for variations in material quality and grading, level of technology, jointing and workmanship.

In Kenya, the Kenya Bureau of Standards is charged with the work of developing, publishing, selling and enforcement of standards. This body has established a timber standardisation panel that draws members from the universities, the Ministry of Public Works and any other interested parties such as the construction industry to assist in the preparation of timber standards. A Kenyan code of practice for structural use of timber is at the draft stage.

Most structural timber designs and specifications in Kenya are carried out to CP112 and, lately, to BS 5268, the former and current British codes of practice for structural use of timber, respectively. The Kenyan timber codes already developed, including the ones in draft stage, have borrowed heavily from the corresponding British standards. For instance KS 02-771, Kenyan Standard Specification for Grading Softwood Timber for Structural Use, is similar to the equivalent British code BS 4978, in many respects.

The most recent grade stresses for Kenyan grown timbers are those given by Harley for pine and cypress. Standard methods of derivation as used in CP112 were used to derive the basic stresses. The single reduction factors applied for some of the strength properties were however different from the values suggested by other researchers and adopted in CP112. The reduction factors and grade ratios applied by Harley are shown in the table below.

Table 2.4 ***Reduction and Grade Factors for Kenya Pines***[11]

Property	**Minimum reduction factor**	**SS Grade Factor (Equivalent Grade Stress)**	**GS Grade Factor (Equivalent Grade Stress)**
Bending parallel to the grains	2.50	0.50	0.35
Comp. parallel to the grains	1.40	(SS bending)	(1.2 x GS bending)
Comp. perpendicular to grains	*	0.75	0.66
Shear parallel to the grains	2.50	0.50	0.50
Mean MOE	1.00	1.00	0.90
Minimum MOE (5% LCL)	1.00	1.00	0.90

*Basic compression perpendicular to grains stress was derived as 0.855/5 times the basic bending stress

2.4.2 STRESS GRADING IN KENYA

The means of assessing the quality of timber in Kenya is principally by the visual stress grading method as covered in KS 02-771:1991, the Kenyan Standard Specification for Softwood Timber Grades for Structural Use. In the KS 02-771 method, strength ratios are applied to basic stresses obtained from small clear specimens to get grade stresses.

Two standard grades of structural timber, namely, the General Structural grade (GS) and Specific Structural grade (SS) have been established in KS 02-771. The strength ratios for KS 02-771 are the same as those for BS 4978 visual strength grades. Two grades of laminated timber have also been established as LA and LB grades. The code allows for a small deviation in grading since it is dependent upon the experience of graders, which may differ. The full details of the grading process can be obtained from the code KS 02-771 or from explanatory notes on the code[16], a report by the MOPW, which also gives the method of assessment of the factors affecting strength.

CHAPTER 3

TEST PROCEDURES

3.0 GENERAL

For the purposes of this research, mechanical strength tests were done on small clear specimens for the determination of the following engineering strength properties:

1 Bending parallel to grains
2 Compression parallel to grains
3 Shear parallel to grains

The modulus of rupture, modulus of elasticity and limit of proportionality were determined from the bending tests. The figure below shows the schematic arrangements for each of these mechanical tests.

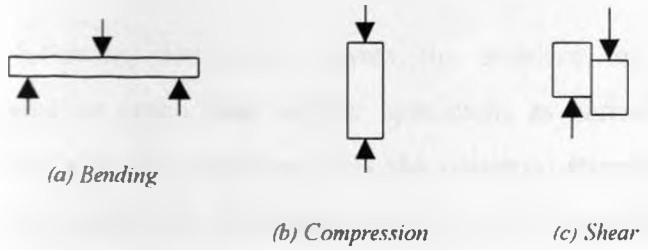

Figure 3.0 Schematic arrangements of the mechanical strength tests

All the tests were done in accordance with BS 373 standard testing procedures for small clear samples. The test specimens were 20×20 mm in cross-section and free from all strength reducing defects.

The specimens were sampled from timber bought from sawmills selected at random within the country, so as to be representative of the whole population. Sixteen sawmills were selected from ten sampling districts. Ten pieces of timber were obtained from each sawmill and a maximum of three specimens was obtained from each piece of timber. The sampling districts and sawmills are shown in appendix F

Testing was carried out for dry conditions with moisture content below 15%, which is the equilibrium moisture content for Kenya. At this state the timber density and dimensional characteristics are stable and do not affect the test results. Supplementary tests for determination of densities and moisture content were carried out for each strength test. The relationship between density and other strengths was sought. Generally the higher the density, the more superior a timber is in strength and stiffness. A high density indicates a high proportion of wood substance, particularly the cell wall material, which gives strength to a timber

A statistical analysis of the test results was then carried out to obtain the necessary information as sought.

3.1 TEST PROCEDURES

The following description covers the standard test procedures for mechanical strengths on small clear timber specimens as carried out in this research. The machine used for these tests was the universal strength-testing machine. For each test, the appropriate accessories were fitted on the machine. For all the tests, samples were labelled appropriately and dimensions and weights were taken before testing commenced. The room temperature and humidity were recorded before any test was done.

3.1.1 STATIC BENDING –CENTER POINT LOADING

Accessories to the universal testing machine for this test were the bending knee, the trunnion supports, deflection yoke and dial gauge (deflectometer). The test specimens measured 20 x 20 x 300mm each. After dimensions and weights were taken, three small nails were driven perpendicular to one tangential face in the neutral plane at the centre and 140mm from the centre. The bending knee was attached to the underside of the moving crosshead and the trunnion supports were fitted on the machine table such that the centre span of the specimen was 280mm. The cross-head was then lowered sufficiently to just touch the specimen, then the deflection yoke supported on the end nails and adjusted to measure deflection of the centre point of the neutral axis. The machine was fitted with plotting accessories, to plot the load-deflection curve. The mode of loading was as shown in figure 2.3 (a). The maximum load was recorded and failure sketched. The mode of failure for this test was splintering or compression failure or horizontal shear. Strength properties from the bending test were determined as follows:

$$MOR = \frac{1.5PL}{bd^2} \quad \text{.......... eq. 3.1}$$

$$MOE = \frac{P'L^3}{4Dbd^3} \quad \text{.......... eq. 3.2}$$

$$LOP = \frac{1.5P'L}{bd^2} \quad \text{.......... eq. 3.3}$$

Where P' = Load at proportional limit (N)

P = Ultimate load (N)

L = Length between beam supports (= 280mm)

b = Width of beam (= 20mm)

d = Depth of beam (= 20mm)

D = Deflection of the neutral plane at LOP (in mm) measured at half span

3.1.2 COMPRESSION PARALLEL TO GRAINS TEST

Specimen for this test measured 20 x 20 x 60mm and was prepared to have faces truly parallel to each other and at right angles to the long axis. A compression platen was fitted to the under side of the moving crosshead of the machine and the test specimen was held in a compression cage assembled on the machine table. Figure 2.3 (b) shows the mode of loading. The load was applied continuously throughout the test at a rate of 0.6 mm per minute crosshead motion. At the point of maximum load and failure, the pointer would retreat to the zero position. At the end of each test, the maximum load was recorded and failure sketched. The mode of failure for this test was either crushing or splitting or brooming and shearing. The strength in compression parallel to grains (C) was obtained as:

$$C = \frac{P}{A} \quad \text{Where } A = \text{Cross-section area of the specimen} \ldots\ldots\ldots\ldots\ldots\ldots \textit{eq. } 3.4$$

3.1.3 SHEAR PARALLEL TO GRAINS TEST

Test specimen was a 20mm cube. At least four samples were tested, two to be sheared radially, and two tangentially. A compression platen was attached to the underside of the moving crosshead of machine and the shear tool was fitted on the machine table to give a loading mode as shown in figure 2.3 (c). The load was applied continuously throughout the test at crosshead motion rate of 0.6mm per minute. At the end of testing, the maximum load was recorded and the failure sketched. The mode of failure was either true or oblique shearing. The strength in shear parallel to grains (S) was obtained as:

$$S = \frac{P}{A} \quad \text{Where } A = \text{Sheared surface area} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{eq. } 3.5$$

CHAPTER 4

RESULTS AND DISCUSSION

4.0 GENERAL

In the foregoing analysis, a normal distribution of test results is assumed. However, there are many occurrences that do not satisfy this assumption strictly and it is almost impossible to state precisely the effect on various statistical procedures if the population distribution differs somewhat from normal. The population may be near normal or is normal but admixed, to some extent, with some other population. Several measures of normality are available but none is generally accepted. Small deviations from normality have a greater effect on some statistical tests and estimates than on others. There are no general statistical rules that apply to every case of non-normality and therefore the choice of methods to use when normality is not assured is something of an art. There is an inherent belief that data in timber engineering should be normal as it is indeed easier to work with percentiles of a specified distribution, hence all derivations are made on the assumption of normal distribution. However, it has been shown that this assumption is not valid for Kenyan pines due to their high variability.

The upper tail in test results for Kenya pines can be attributed to a high proportion of compression wood ranging between 10% to 30%[7]. The general trend of strength histograms was as shown in figure 3.1.

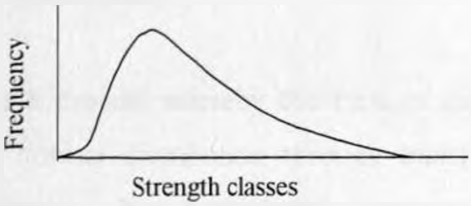

Figure 4.0 The general trend of results histograms

This trend indicates that the pine population is admixed, the main population being specimens free of compression wood and a secondary population being specimens with compression wood. This explains the positive skew and wide scatter of the test results. The ideal solution would be to isolate compression wood specimens in the derivations but this proved very difficult due to the following factors:

i) Identification of compression wood was only apparent at the ends (transverse face) and not the sides, making it difficult to isolate it visually in long specimens for bending and compression parallel to grains.

ii) Compression wood is present in mixed proportions, not following any pattern, such that a specimen with 100% compression wood at one end may have little or none at the other end. A single specimen may have varying proportion of compression wood along its cross-section. This made it very difficult to isolate compression wood specimens and to judge the extent to which it is found in a specimen. Its effect in a given specimen was difficult to establish as it also depends on its location on the specimen, whether at the edge or centre of the cross-section.

Results from tests on compression wood specimens were only indicative, but sufficient to show that they were the cause of the skewness and large scatter of distributions. While not wishing to break with the standard methods of derivation, the solution to non-normality problem in Kenya pines has been approached here through normalization of data. This is considered suitable since the form of non-normality observed from test results was of a specific form where all the distributions had a positive skew with an exceptionally large scatter.

4.1 NORMALIZATION

Normalization is a process whereby the form of distribution is made to agree with assumptions of normal distribution through transformation of data or any other appropriate procedure. Two normalization techniques have been adopted, namely; *data trimming* and *data transformation*.

4.1.1 DATA TRIMMING

Trimming involves discarding of extreme observations which could have resulted from gross errors, blunders or from a population other than the test population, or those that could have resulted from the fact that the population under investigation contains a certain proportion of extreme cases. Trimming the upper tail cannot result in danger of overestimating the strength of timber since it is an expected minimum value that is used in derivation of basic stress. Indeed this would lead to conservatism in the derived grade stresses, as this does not take advantage of the extremely high values.

The trimming value was obtained as follows:

1. For each strength, a value *k* was determined as the ratio of the difference between the mean and lowest strength (x_{min}) to the standard deviation using the expression:

$$k = \frac{\mu - x_{\min}}{\sigma} \qquad \text{eq 4.1}$$

2. The k values were found to be of the same range and the average *k* value for all the strengths in the test program was then calculated.
3. The average value of *k*, found to be equal to 2, was then used as the basis for obtaining the trimming values x_t given in table 3.1 using the formula:

$$x_t = \mu + 2 \times \sigma \qquad \text{eq 4.2}$$

4. Values higher than x_t were omitted from the test data.

Table 4.1 ***Data Trimming Values***

Property	**μ (N/mm^2)**	**σ (N/mm^2)**	**K value**	**x_t (N/mm^2)**
Modulus of rupture	75.710	25.123	1.965	125.956
Modulus of elasticity	94508	36310	1.680	167128
Compression parallel	49.086	16.684	1.729	82.455
Shear parallel	13.442	3.480	2.226	20.401

4.1.2 DATA TRANSFORMATION

Since the test distributions are positively skewed, the data transformation should be such that the values in the upper tail are reduced by a bigger margin compared to those at the lower end. A suitable transformation is the logarithmic transformation commonly used in statistics, in which each measurement is replaced by its logarithm. An approximately straight cumulative distribution polygon on a graph paper with a logarithmic scale on one axis and a normal probability scale on the other, is an indication of normality of the transformed observations.

4.2 PRESENTATION OF RESULTS

4.2.1 GENERAL

The laboratory test results for each specimen have been included in the appendix, showing the specimen number, the strength, the density and the moisture content at the time of test.

The data has been analysed and presented for three cases, which are;

1. Direct results
2. Trimmed data
3. Transformed data

The test results and analysis for each of the strength properties have been lumped together in the tables that follow for ease of comparison between the proposed three methods of stress derivations for Kenya pines. The strength properties reported are:

I. Modulus of rupture
II. Modulus of elasticity
III. Compression parallel to grains
IV. Shear parallel to grains

Three methods have been used to test the fitness of actual distributions to the normal distribution. Each of these tests is described below;

(i) Visual inspection of histogram superimposed with normal curve

The normal curve is fitted onto the histogram, and adjusted such that it has approximately the same area as the histogram. The formula below is used:

$$y = \frac{Nl}{\sigma\sqrt{2\pi}} e^{\frac{1}{2}\left(\frac{X_i - \mu}{\sigma}\right)^2} \quad \text{......} \quad eq.\ 4.3$$

Where y = Normal distribution value

(ii) Visual inspection of cumulative distribution polygon

The actual cumulative distribution polygon is plotted on the same scale as the cumulative normal distribution for a visual inspection of the fit. The correlation coefficient between the two curves is also obtained as a measure of the goodness of fit. For normally distributed actual results, the two curves coincide with a correlation coefficient equal to one.

(iii) Formal test of skewness

The degree of asymmetry about the mean for each distribution has been determined as the skewness using the formula;

$$Skewness = \frac{N}{(N-1)(N-2)}\sum\left(\frac{X_i - \overline{X}}{\sigma}\right)^3 \qquad \text{eq. 4.4}$$

The skewness of a normal distribution curve is zero. The higher the skewness in either the positive or the negative, the greater the degree of non-normality. Skewness is used here as a comparative index to show the closeness to normality.

4.2.2 REDUCTION FACTORS

Since there has been no testing on Kenyan pines to establish the appropriate reduction factors to cater for the effects of load duration, depth and safety, the factors derived for tropical timbers in Australian derivation procedures have been taken as suitable. The combined reduction factors used in this derivation are thus 2.65 for both bending and shear, rather than the 2.5 value used by Harley, and 2.0 for compression parallel to grains, rather than 1.4 used by Harley. The use of different reduction factors can only be justified through controlled testing.

All the stresses given in the following tables are in N/mm^2.

4.2.3 MODULUS OF RUPTURE RESULTS

Table 4.2.3-1 Direct MOR Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal ditribution x202x10	Cummulative normal (%)
1	x<=25	20	0	0.000	0.001	2.744	1.359
2	25<x<=35	30	3	1.485	0.003	6.129	4.393
3	35<x<=45	40	17	9.901	0.006	11.681	10.175
4	45<x<=55	50	25	22.277	0.009	19.001	19.582
5	55<x<=65	60	36	40.099	0.013	26.380	32.641
6	65<x<=75	70	27	53.465	0.015	31.259	48.116
7	75<x<=85	80	34	70.297	0.016	31.612	63.765
8	85<x<=95	90	20	80.198	0.014	27.285	77.273
9	95<x<=105	100	12	86.139	0.010	20.100	87.224
10	105<x<=115	110	10	91.089	0.006	12.637	93.480
11	115<x<=125	120	9	95.545	0.003	6.781	96.837
12	125<x<=135	130	5	98.020	0.002	3.106	98.374
13	135<x<=145	140	1	98.515	0.001	1.214	98.975
14	145<x<=155	150	2	99.505	0.000	0.405	99.176
15	155<x<=165	160	1	100.000	0.000	0.115	99.233
16	x>165	170	0	100.000	0.000	0.028	99.247

No. of specimens	202
Arthmetic mean	75.759
Standard deviation	25.271
1%LCL	16.878
Skewness	0.74

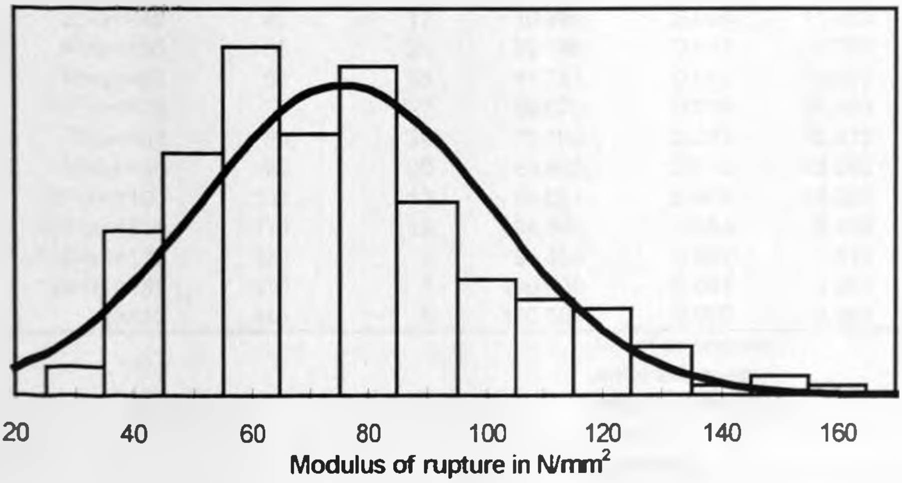

Figure 4.2.3-1 Direct MOR Histogram with Superimposed Normal

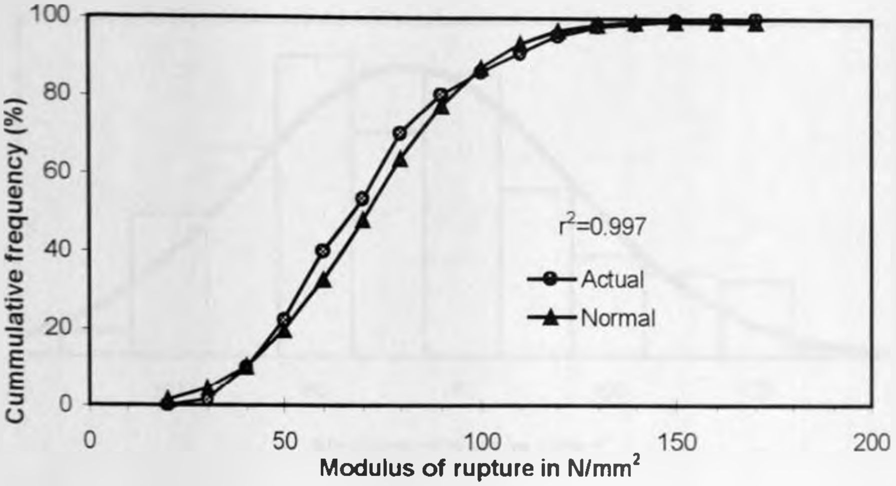

Figure 4.2.3-2 Direct MOR Cumulative Distribution Curves

Table 4.2.3-2 Trimmed MOR Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal ditribution x194x10	Cummulative normal (%)
1	x<=25	20	0	0.000	0.001	2.160	1.114
2	25<x<=35	30	3	1.546	0.003	5.619	4.010
3	35<x<=45	40	17	10.309	0.006	11.953	10.171
4	45<x<=55	50	25	23.196	0.011	20.798	20.892
5	55<x<=65	60	36	41.753	0.015	29.602	36.150
6	65<x<=75	70	27	55.670	0.018	34.463	53.915
7	75<x<=85	80	34	73.196	0.017	32.819	70.832
8	85<x<=95	90	20	83.505	0.013	25.565	84.010
9	95<x<=105	100	12	89.691	0.008	16.289	92.406
10	105<x<=115	110	10	94.845	0.004	8.489	96.782
11	115<x<=125	120	9	99.485	0.002	3.619	98.648
12	125<x<=135	130	1	100.000	0.001	1.262	99.298
13	x>135	140	0	100.000	0.000	0.360	99.484

No. of specimens	194
Arthmetic mean	72.568
Standard deviation	22.309
1%LCL	20.588
Skewness	0.329

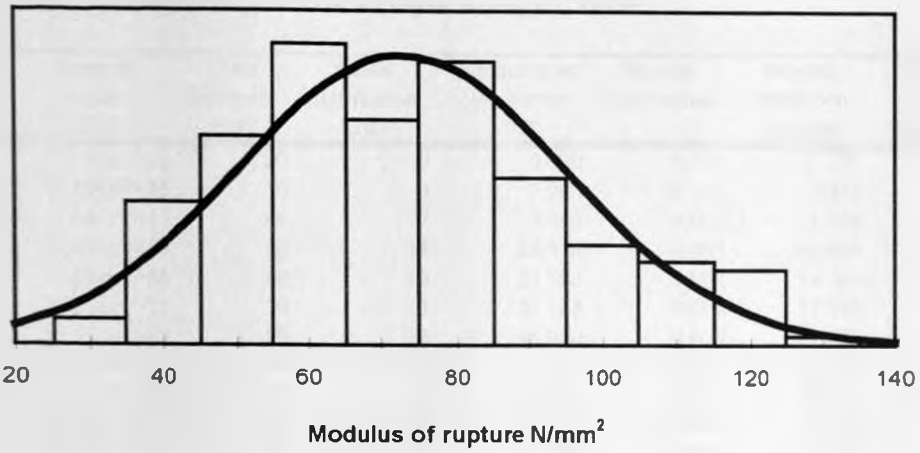

Figure 4.2.3-3 Trimmed MOR Histogram with Superimposed Normal

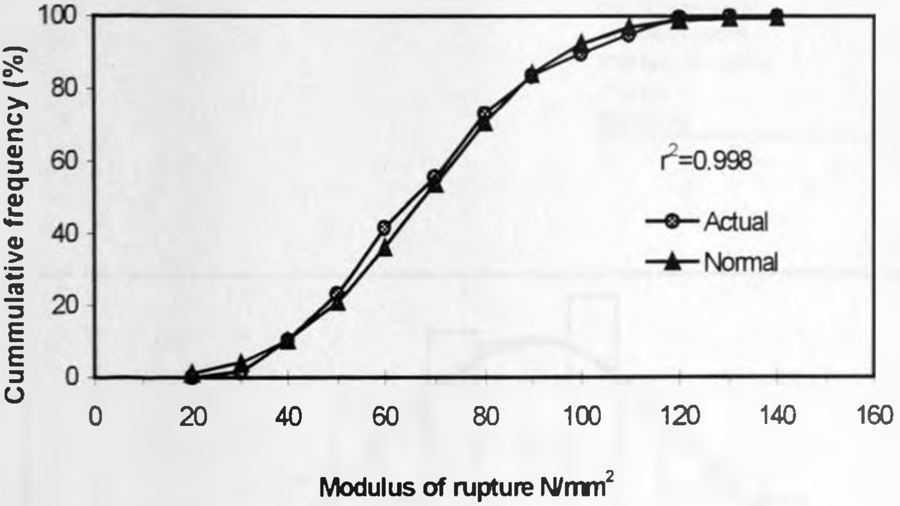

Figure 4.2.3-4 Trimmed MOR Cumulative Distribution Curves

Table 4.2.3-3 Transformed MOR Results Analysis Table

	Strength classes x102	Class midpoint x102	Actual distribution x102	Cummulative distribution x102	Normal distribution	Normal ditribution x202x10	Cummulative normal distribution
2	15<x<=25	20	0	0.000	0.001	2.539	1.257
3	25<x<=35	30	4	1.980	0.002	4.405	3.438
4	35<x<=45	40	7	5.446	0.003	7.056	6.931
5	45<x<=55	50	14	12.376	0.005	10.440	12.099
6	55<x<=65	60	19	21.782	0.007	14.264	19.160
7	65<x<=75	70	23	33.168	0.009	17.998	28.070
8	75<x<=85	80	26	46.040	0.010	20.973	38.453
9	85<x<=95	90	25	58.416	0.011	22.571	49.626
10	95<x<=155	100	13	64.851	0.011	22.432	60.731
11	155<x<=115	110	17	73.267	0.010	20.589	70.924
12	115<x<=125	120	15	80.693	0.009	17.452	79.564
13	125<x<=135	130	11	86.139	0.007	13.662	86.327
14	135<x<=145	140	5	88.614	0.005	9.877	91.217
15	145<x<=155	150	9	93.069	0.003	6.594	94.481
16	155<x<=165	160	5	95.545	0.002	4.066	96.494
17	165<x<=175	170	3	97.030	0.001	2.315	97.640
18	175<x<=185	180	4	99.010	0.001	1.217	98.243
19	185<x<=195	190	2	100.000	0.000	0.591	98.535
20	x>195	200	0	100.000	0.000	0.265	98.667

No. of specimens	202
Arthmetic mean	9423
Standard deviation	3545
1%LCL	1163
Skewness	0.588

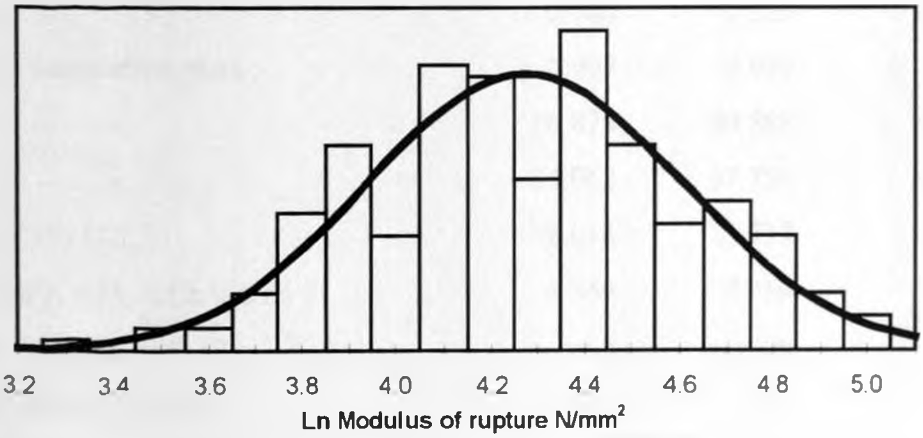

Figure 4.2.3-5 Transformed MOR Histogram with Superimposed Normal

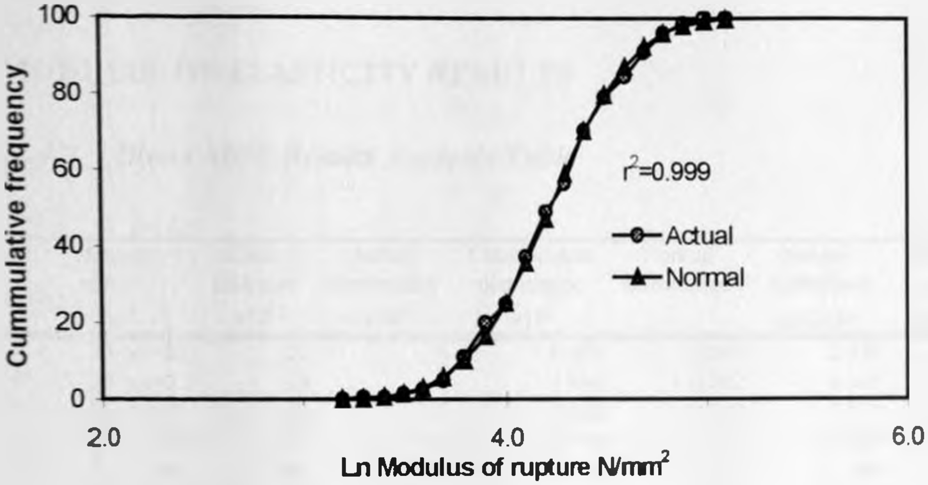

Figure 4.2.3-6 Transformed MOR Cumulative Distribution Curves

Table 4.2.3-4 Summary of MOR Test Results

Property	**Direct results**	**Trimmed data**	**Transformed data**
μ	75.759	72.568	71.792
σ	25.271	22.309	16.620
CV	33.4	30.7	23.1
skewness	0.740	0.329	-0.091
r^2 between cumulative plots	0.997	0.998	0.999
1% LCL	16.878	20.588	33.067
5% LCL	34.062	37.758	41.463
5% LCL ÷ 1% LCL	2.018	1.737	1.254
Basic stress f_b = 1% LCL ÷ 2.65	6.369	7.769	12.478
SS grade stress f_b x 0.5	3.2	3.9	6.2
GS grade stress = f_b x 0.35	2.2	2.7	4.4

1. The ratio 5%LCL÷1% LCL is observed to vary widely for the three data cases. The value of 1.254 for transformed data is closest to the BS 5268 value of 1.2

2. The grade stresses for transformed data compare well with those for pines from other regions shown in table 1.2.

4.2.4 MODULUS OF ELASTICITY RESULTS

Table 4.2.4-1 Direct MOE Results Analysis Table

	Strength classes $x10^2$	Class midpoint $x10^2$	Actual distribution $x10^2$	Cummulative distribution $x10^2$	Normal distribution	Normal ditribution x202x10	Cummulative normal distribution
2	15<x<=25	20	0	0.000	0.001	2.539	1.257
3	25<x<=35	30	4	1.980	0.002	4.405	3.438
4	35<x<=45	40	7	5.446	0.003	7.056	6.931
5	45<x<=55	50	14	12.376	0.005	10.440	12.099
6	55<x<=65	60	19	21.782	0.007	14.264	19.160
7	65<x<=75	70	23	33.168	0.009	17.998	28.070
8	75<x<=85	80	26	46.040	0.010	20.973	38.453
9	85<x<=95	90	25	58.416	0.011	22.571	49.626
10	95<x<=155	100	13	64.851	0.011	22.432	60.731
11	155<x<=115	110	17	73.267	0.010	20.589	70.924
12	115<x<=125	120	15	80.693	0.009	17.452	79.564
13	125<x<=135	130	11	86.139	0.007	13.662	86.327
14	135<x<=145	140	5	88.614	0.005	9.877	91.217
15	145<x<=155	150	9	93.069	0.003	6.594	94.481
16	155<x<=165	160	5	95.545	0.002	4.066	96.494
17	165<x<=175	170	3	97.030	0.001	2.315	97.640
18	175<x<=185	180	4	99.010	0.001	1.217	98.243
19	185<x<=195	190	2	100.000	0.000	0.591	98.535
20	x>195	200	0	100.000	0.000	0.265	98.667
					No. of specimens		202
					Arthmetic mean		9423
					Standard deviation		3545
					1%LCL		1163
					Skewness		0.588

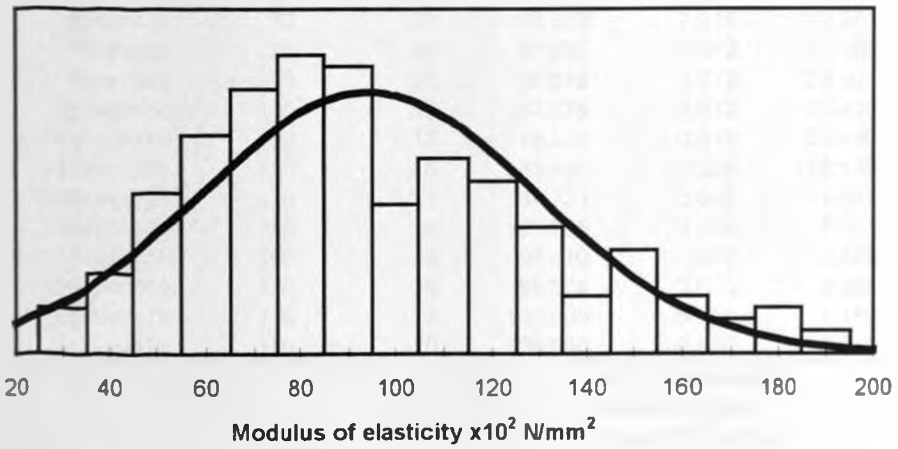

Figure 4.2.4-1 Direct MOE Histogram with Superimposed Normal

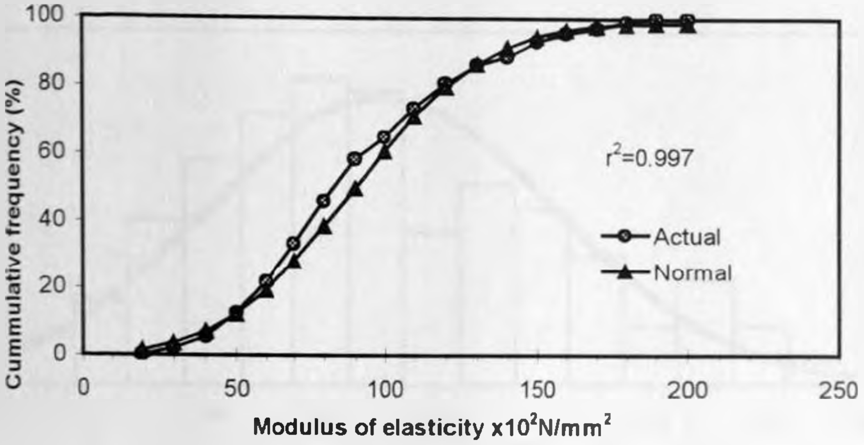

Figure 4.2.4-2 Direct MOE Cumulative Distribution Curves

Table 4.2.4-2 Trimmed MOE Results Analysis Table

	Strength classes $x10^2$	Class midpoint $x10^2$	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal ditribution x195x10	Cummulative normal (%)
1	x<=25	20	0	0.000	0.001	2.046	1.049
2	25<x<=35	30	4	2.051	0.002	3.909	3.054
3	35<x<=45	40	7	5.641	0.003	6.771	6.526
4	45<x<=55	50	14	12.821	0.005	10.636	11.980
5	55<x<=65	60	19	22.564	0.008	15.148	19.748
6	65<x<=75	70	23	34.359	0.010	19.563	29.781
7	75<x<=85	80	26	47.692	0.012	22.908	41.528
8	85<x<=95	90	25	60.513	0.012	24.324	54.002
9	95<x<=155	100	13	67.179	0.012	23.420	66.012
10	155<x<=115	110	17	75.897	0.010	20.446	76.497
11	115<x<=125	120	15	83.590	0.008	16.185	84.798
12	125<x<=135	130	11	89.231	0.006	11.618	90.755
13	135<x<=145	140	5	91.795	0.004	7.561	94.633
14	145<x<=155	150	9	96.410	0.002	4.463	96.921
15	155<x<=165	160	5	98.974	0.001	2.388	98.146
16	165<x<=175	170	2	100.000	0.001	1.159	98.740
17	x>175	180	0	100.000	0.000	0.510	99.002

No. of specimens	195
Arthmetic mean	9113
Standard deviation	3196
1%LCL	1666
Skewness	0.416

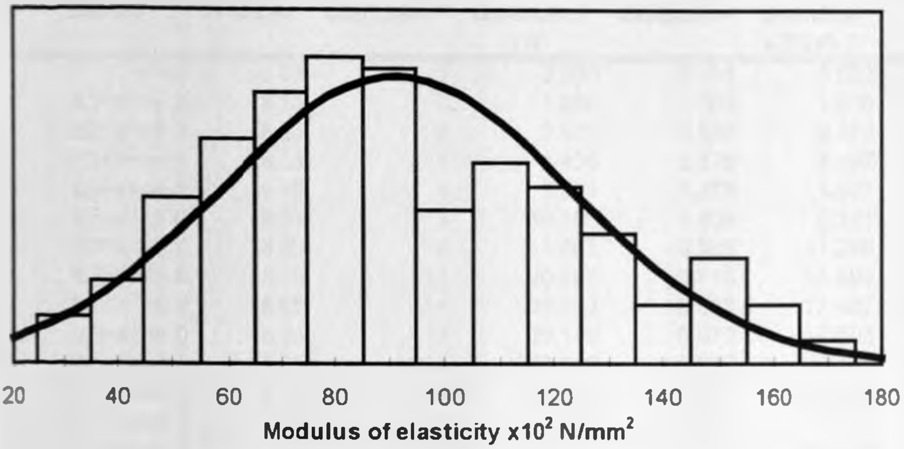

Figure 4.2.4-3 ***Trimmed MOE Histogram with Superimposed Normal***

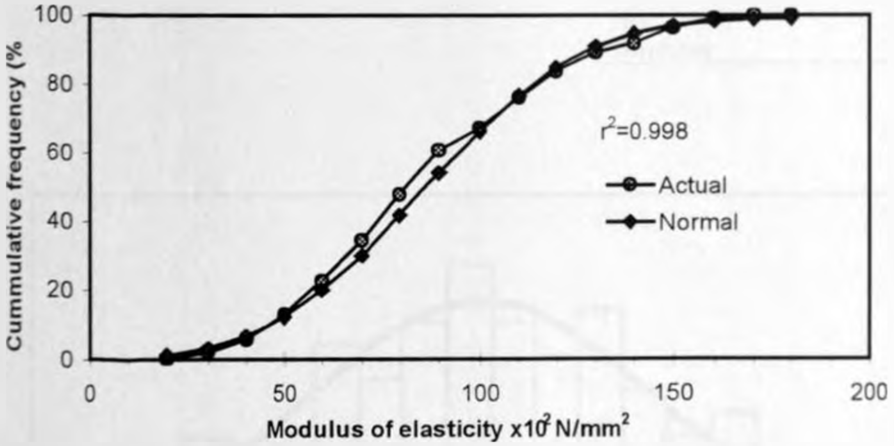

Figure 4.2.4-4 ***Trimmed MOE Cumulative Distribution Curves***

Table 4.2.4-3 Transformed MOE Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal ditribution x202x0.1	Cummulative normal (%)
1	x<=8	8.05	0	0.000	0.031	0.632	0.313
2	8.1<x<=8.2	8.15	6	1.980	0.060	1.206	0.910
3	8.2<x<=8.3	8.25	2	2.970	0.107	2.153	1.976
4	8.3<x<=8.4	8.35	1	4.455	0.178	3.597	3.756
5	8.4<x<=8.5	8.45	9	5.941	0.279	5.627	6.542
6	8.5<x<=8.6	8.55	5	10.396	0.408	8.241	10.622
7	8.6<x<=8.7	8.65	8	13.861	0.559	11.299	16.216
8	8.7<x<=8.8	8.75	17	20.297	0.718	14.503	23.396
9	8.8<x<=8.9	8.85	14	26.733	0.863	17.427	32.023
10	8.9<x<=9.0	8.95	19	35.149	0.970	19.603	41.727
11	9.0<x<=9.1	9.05	24	46.040	1.022	20.643	51.946
12	9.1<x<=9.2	9.15	19	56.931	1.007	20.351	62.021
13	9.2<x<=9.3	9.25	16	64.851	0.930	18.782	71.319
14	9.3<x<=9.4	9.35	20	73.267	0.803	16.227	79.352
15	9.4<x<=9.5	9.45	13	82.178	0.650	13.125	85.850
16	9.5<x<=9.6	9.55	9	87.624	0.492	9.938	90.770
17	9.6<x<=9.7	9.65	11	93.069	0.349	7.045	94.257
18	9.7<x<=9.8	9.75	6	97.030	0.231	4.675	96.571
19	9.8<x<=9.9	9.85	3	99.010	0.144	2.904	98.009
20	9.9<x<=10	9.95	0	100.000	0.084	1.689	98.845
21	x>10	10.05	0	100.000	0.046	0.920	99.301

No. of specimens	202
Arthmetic mean	9.078
Standard deviation	0.389
1%LCL	8.171
Skewness	-0.275

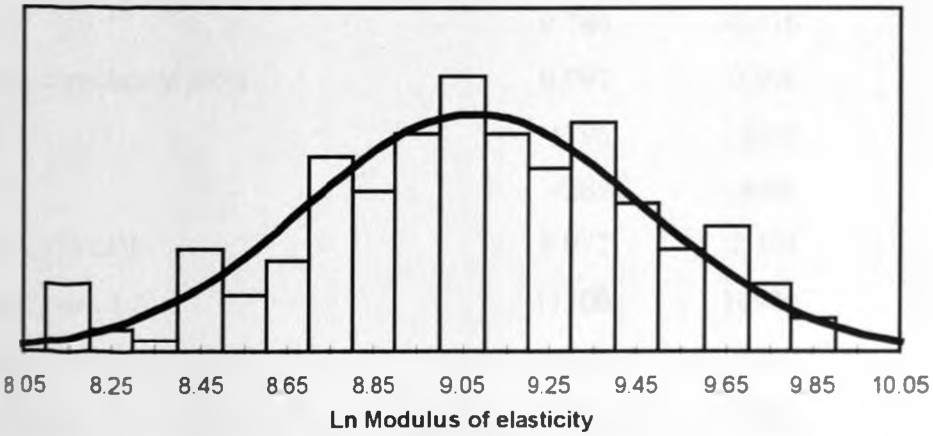

Figure 4.2.4-5 Transformed MOE Histogram with Superimposed Normal

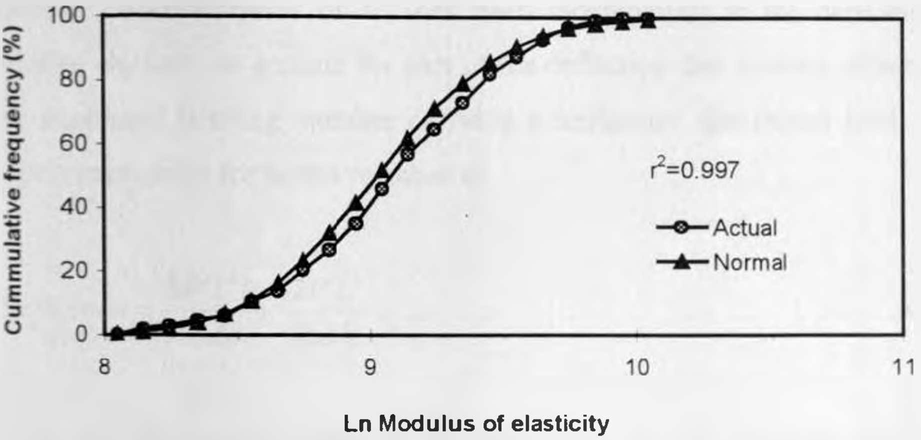

Figure 4.2.4-6 Transformed MOE Cumulative Distribution Curves

Table 4.2.4-4 Summary of MOE Test Results

Property	Direct results	Trimmed data	Transformed data
μ x 1.2 (Shear correction factor)	11308	10936	10517
σ x 1.2 (Shear correction factor)	4254	3835	2692
CV	37.7	35.1	25.6
skewness	0.740	0.416	-0.275
r^2 between cumulative plots	0.997	0.998	0.997
1% LCL	1396	2000	3538
5% LCL	4289	4608	4610
5% LCL ÷ 1% LCL	3.072	2.304	1.303
SS mean E =μ x 1.0	11300	10900	10500
GS mean E =μ x 0.9	10200	9800	9500
SS minimum E = 5% LCL x 1.0	4300	4600	4600
GS minimum E = 5% LCL x 0.9	3900	4100	4100

1. The shear correction factor of 1.2 has been incorporated in the derivation of modulus of elasticity to account for part of the deflection due to shear effects in a simply supported bending member carrying a uniformly distributed load. The deflection expression for such a member is:

$$Deflection = \frac{5P'L^4}{384EI} + \frac{12P'L^2}{5Ebh} \quad \text{.........} eq.\ 4.5$$

The first and the second parts of the expression are the bending and shear deflections respectively. The 1.2 value was found appropriate following full-sized testing which avoids inclusion of deflection due to shear effects[14].

2. The coefficient of variation is high and thus the 1% LCL values are low and the 5% LCL values have been used to calculate the MOE minimum values in conformity to the BS 5268 method.

3. The correlation coefficient r is almost the same for the raw, trimmed and transformed data cases and there is thus little difference in both the 1% LCL and the 5% LCL values for the three cases. The grade stresses are also almost the same for the three data cases.

4. The ratio 5%LCL÷1% LCL is observed to vary widely for the three data cases. The value of 1.3 for transformed data is closest to the BS 5268 value of 1.2.

4.2.5 COMPRESSION PARALLEL TO GRAINS

Table 4.2.5-1 Direct Compression Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x302x5	Cummulative normal (%)
1	12.5<x<=17.5	10	0	0.000	0.002	2.322	0.769
2	17.5<x<=22.5	15	5	1.656	0.003	4.480	2.252
3	22.5<x<=27.5	20	22	8.940	0.005	7.900	4.868
4	27.5<x<=32.5	25	29	18.543	0.008	12.736	9.085
5	32.5<x<=37.5	30	29	28.146	0.012	18.768	15.300
6	37.5<x<=42.5	35	31	38.411	0.017	25.281	23.671
7	42.5<x<=47.5	40	40	51.656	0.021	31.130	33.978
8	47.5<x<=52.5	45	32	62.252	0.023	35.039	45.581
9	52.5<x<=57.5	50	28	71.523	0.024	36.052	57.518
10	57.5<x<=62.6	55	16	76.821	0.022	33.908	68.746
11	62.5<x<=67.6	60	16	82.119	0.019	29.152	78.399
12	67.7<x<=72.7	65	17	87.748	0.015	22.910	85.985
13	72.7<x<=77.7	70	18	93.709	0.011	16.458	91.435
14	77.5<x<=82.5	75	11	97.351	0.007	10.808	95.014
15	82.5<x<=87.5	80	5	99.007	0.004	6.488	97.162
16	87.5<x<=92.5	85	2	99.669	0.002	3.560	98.341
17	92.5<x<=97.5	90	1	100.000	0.001	1.786	98.932
18	x>97.5	95	0	100.000	0.001	0.819	99.203

No. of specimens	302
Arthmetic mean	49.086
Standard deviation	16.684
1%LCL	10.212
Skewness	0.439

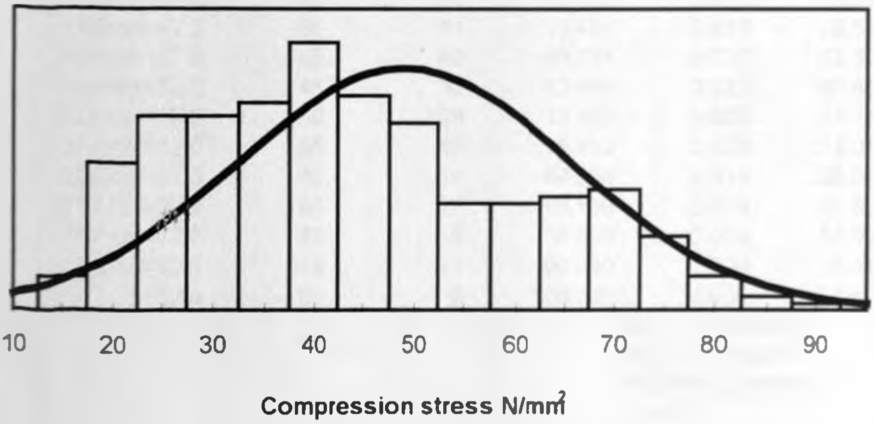

Figure 4.2.5-1 Direct Compression Histogram with Superimposed Normal

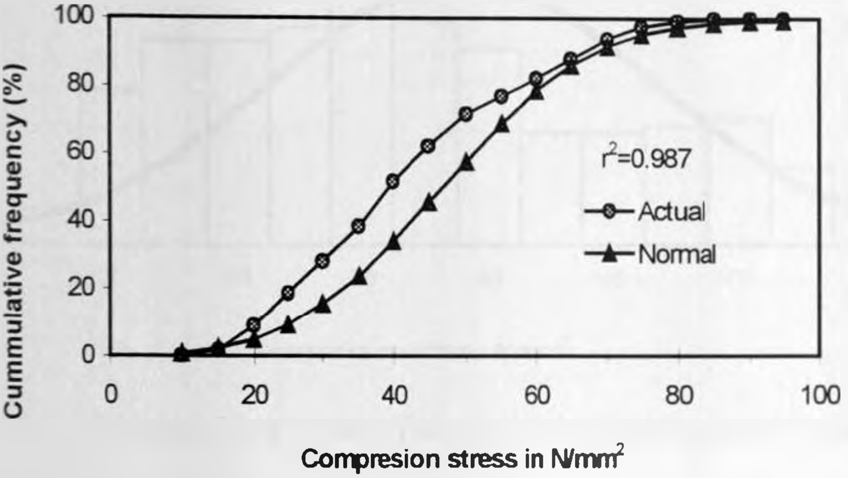

Figure 4.2.5-2 Direct Compression Cumulative Distribution Curves

Table 4.2.5-2 Trimmed Compression Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x294x5	Cummulative normal (%)
1	12.5<x<=17.5	10	0	0.000	0.001	1.928	0.656
2	17.5<x<=22.5	15	5	1.701	0.003	3.999	2.016
3	22.5<x<=27.5	20	22	9.184	0.005	7.485	4.562
4	27.5<x<=32.5	25	29	19.048	0.009	12.645	8.863
5	32.5<x<=37.5	30	29	28.912	0.013	19.276	15.419
6	37.5<x<=42.5	35	31	39.456	0.018	26.518	24.439
7	42.5<x<=47.5	40	40	53.061	0.022	32.921	35.637
8	47.5<x<=52.5	45	32	63.946	0.025	36.881	48.181
9	52.5<x<=57.5	50	28	73.469	0.025	37.286	60.864
10	57.5<x<=62.6	55	16	78.912	0.023	34.017	72.434
11	62.5<x<=67.6	60	16	84.354	0.019	28.005	81.960
12	67.7<x<=72.7	65	17	90.136	0.014	20.807	89.037
13	72.7<x<=77.7	70	18	96.259	0.009	13.950	93.781
14	77.5<x<=82.5	75	11	100.000	0.006	8.440	96.652
15	x>82.5	80	0	100.000	0.003	4.608	98.220
					No of specimens		294
					Arthmetic mean		48.031
					Standard deviation		15.604
					1%LCL		11.675
					Skewness		0.324

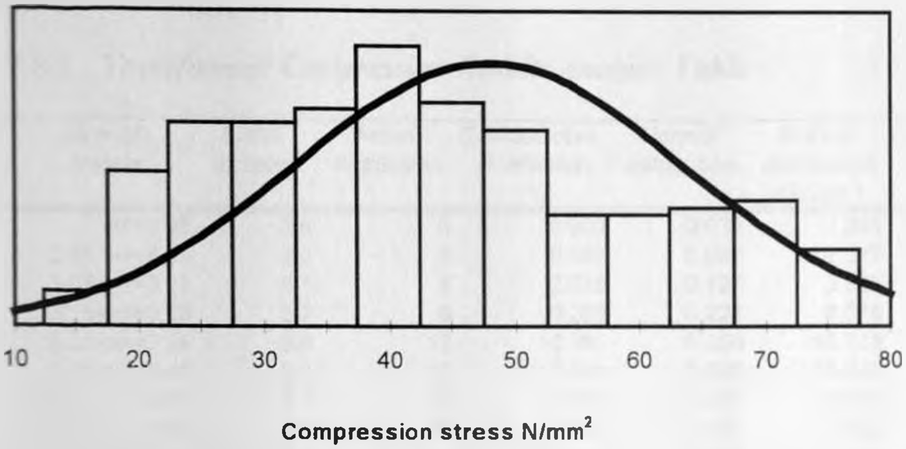

Figure 4.2.5-1 Trimmed Compression Histogram with Superimposed Normal

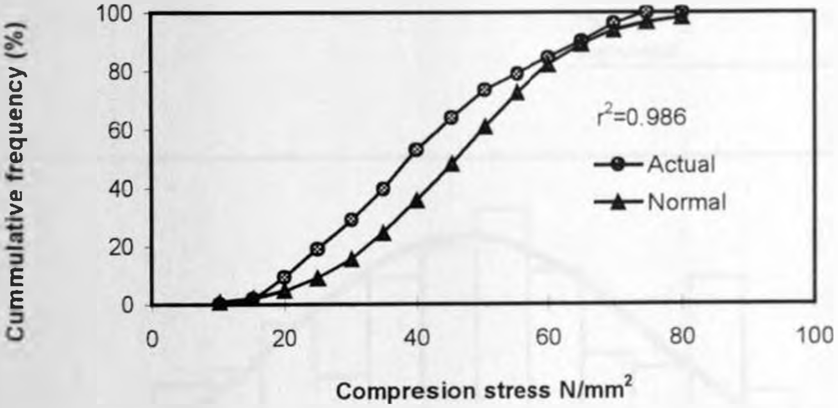

Figure 4.2.5-2 Trimmed Compression Cumulative Distribution Curves

Table 4.2.5-3 ***Transformed Compression Results Analysis Table***

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x302x0.1	Cummulative normal (%)
1	x<=2.95	2.9	0	0.000	0.032	0.981	0.325
2	2.95<x<=3.05	3.0	3	0.993	0.067	2.017	0.993
3	3.05<x<=3.15	3.1	4	2.318	0.127	3.822	2.258
4	3.15<x<=3.25	3.2	9	5.298	0.221	6.676	4.469
5	3.25<x<=3.35	3.3	15	10.265	0.356	10.748	8.028
6	3.35<x<=3.45	3.4	17	15.894	0.528	15.950	13.309
7	3.45<x<=3.55	3.5	23	23.510	0.722	21.816	20.533
8	3.55<x<=3.65	3.6	16	28.808	0.911	27.505	29.640
9	3.65<x<=3.75	3.7	29	38.411	1.058	31.962	40.224
10	3.75<x<=3.85	3.8	33	49.338	1.134	34.234	51.560
11	3.85<x<=3.95	3.9	38	61.921	1.119	33.797	62.751
12	3.95<x<=4.05	4.0	30	71.854	1.018	30.754	72.934
13	4.05<x<=4.05	4.1	19	78.146	0.854	25.794	81.475
14	4.15<x<=4.25	4.2	17	83.775	0.660	19.941	88.078
15	4.25<x<=4.35	4.3	29	93.377	0.470	14.209	92.783
16	4.35<x<=4.45	4.4	14	98.013	0.309	9.332	95.873
17	4.45<x<=4.55	4.5	6	100.000	0.187	5.649	97.744
18	x>4.55	4.6	0	100.000	0.104	3.152	98.788

No. of specimens	302
Arthmetic mean	3.834
Standard deviation	0.350
1%LCL	3.018
Skewness	-0.198

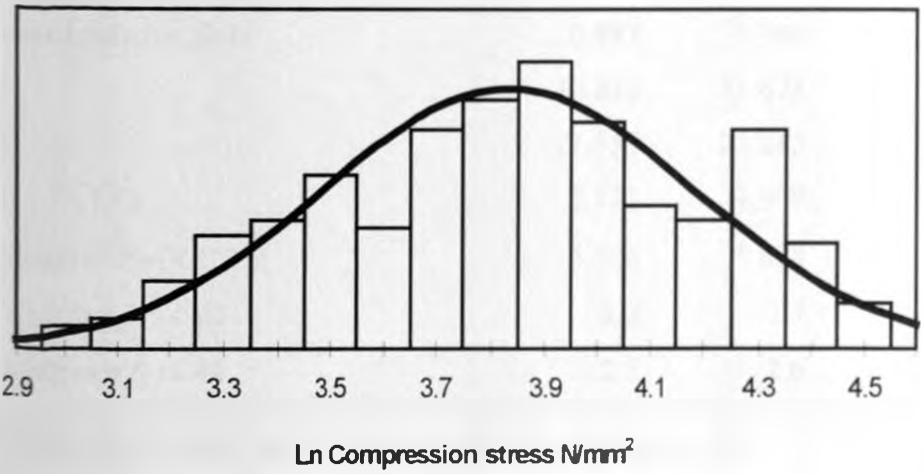

Figure 4.2.5-3 ***Transformed Compression Histogram with Superimposed Normal***

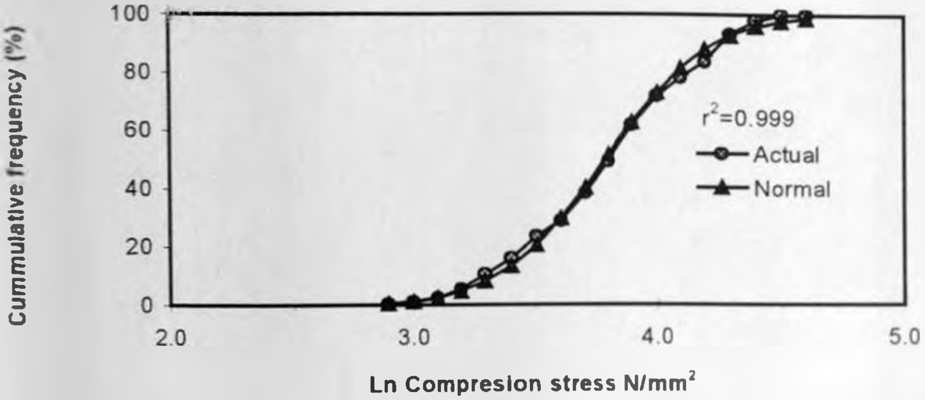

Figure 4.2.5-3 Transformed Compression Cumulative Distribution Curves

Table 4.2.5-4 Summary of Compression Parallel to Grains Test Results

Property	**Direct results**	**Trimmed data**	**Transformed data**
μ	49.086	48.031	46.260
σ	16.684	15.604	11.075
C V	34.0	32.5	23.9
skewness	0.439	0.324	-0.198
r^2 between cumulative plots	0.987	0.986	0.999
1% LCL	10.212	11.675	20.454
5% LCL	21.557	22.285	25.954
5% LCL ÷ 1% LCL	2.111	1.909	1.269
Basic stress f_b = 1% LCL ÷ 2	5.106	5.838	10.227
SS grade stress = f_b x 0.63	3.2	3.7	6.4
GS grade stress = f_b x0.44	2.2	2.6	4.5

1 There is a distinct upper tail in the direct results resulting in high CV values

2 The correlation coefficient, r^2 is closest to unity for the transformed data

3 CV values for direct and trimmed data are much higher than for transformed data

4 The value of 1.269 for transformed data is closest to the BS 5268 value of 1.2

5 Compression parallel to grains is the strength most affected by reaction wood

4.2.6 SHEAR PARALLEL TO GRAINS

Table 4.2.6-1 ***Direct Shear Results Analysis Table***

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x507x1	Cummulative normal (%)
2	4.5<x<=5.5	5	0	0.000	0.006	3.012	0.594
3	5.5<x<=6.5	6	2	0.394	0.012	5.812	1.740
4	6.5<x<=7.5	7	3	0.986	0.021	10.324	3.777
5	7.5<x<=8.5	8	15	3.945	0.034	16.882	7.106
6	8.5<x<=9.5	9	31	10.059	0.051	25.413	12.119
7	9.5<x<=10.5	10	55	20.907	0.070	35.217	19.065
8	10.5<x<=11.5	11	69	34.517	0.090	44.926	27.926
9	11.5<x<=12.5	12	57	45.759	0.105	52.759	38.332
10	12.5<x<=13.5	13	43	54.241	0.114	57.037	49.582
11	13.5<x<=62.6	14	52	64.497	0.113	56.764	60.778
12	14.5<x<=15.5	15	55	75.345	0.104	52.005	71.036
13	15.5<x<=16.5	16	37	82.643	0.088	43.860	79.686
14	16.5<x<=17.5	17	27	87.968	0.068	34.053	86.403
15	17.5<x<=18.5	18	19	91.716	0.049	24.339	91.204
16	18.5<x<=19.5	19	10	93.688	0.032	16.014	94.362
17	19.5<x<=20.5	20	12	96.055	0.019	9.699	96.275
18	20.5<x<=21.5	21	5	97.041	0.011	5.408	97.342
19	21.5<x<=22.5	22	7	98.422	0.006	2.776	97.889
20	22.5<x<=23.5	23	4	99.211	0.003	1.312	98.148
21	23.5<x<=24.5	24	1	99.408	0.001	0.571	98.261
22	24.5<x<=25.5	25	2	99.803	0.000	0.228	98.306
23	25.5<x<=26.5	26	1	100.000	0.000	0.084	98.322
24	x>26.5	27	0	100.000	0.000	0.029	98.328

No. of specimens	507
Arthmetic mean	13.442
Standard deviation	3.476
1%LCL	5.343
Skewness	0.728

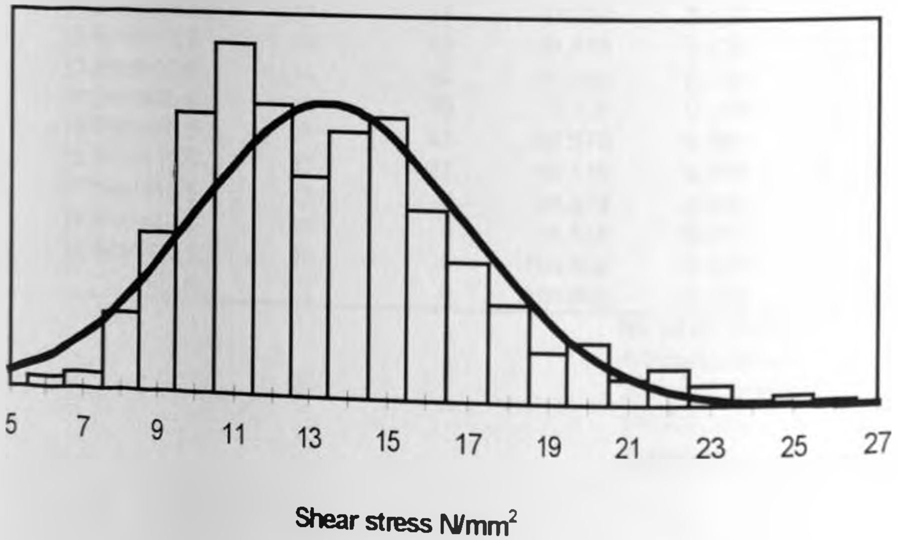

Figure 4.2.6-1 Direct Shear Histogram with Superimposed Normal

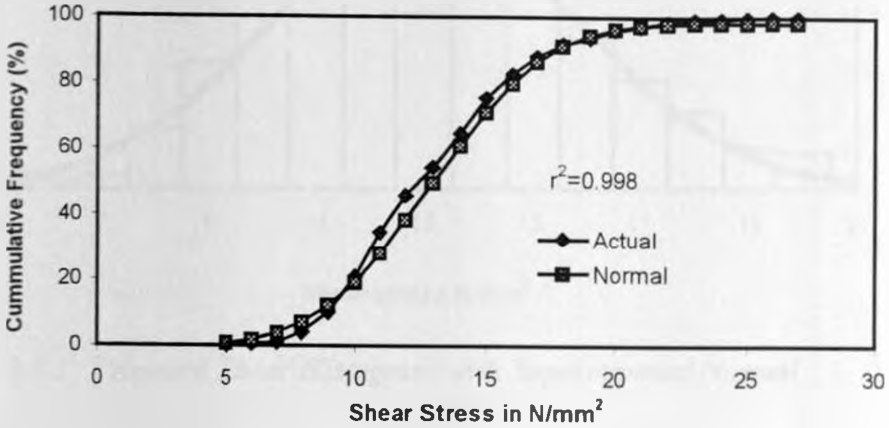

Figure 4.2.6-2 Direct Shear Cumulative Distribution Curves

Table 4.2.6-2 Trimmed Shear Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x484x1	Cummulative normal (%)
1	4.5<x<=5.5	5	0	0.000	0.003	1.611	0.333
2	5.5<x<=6.5	6	2	0.413	0.008	3.832	1.125
3	6.5<x<=7.5	7	3	1.033	0.017	8.120	2.802
4	7.5<x<=8.5	8	15	4.132	0.032	15.337	5.971
5	8.5<x<=9.5	9	31	10.537	0.053	25.815	11.305
6	9.5<x<=10.5	10	55	21.901	0.080	38.728	19.306
7	10.5<x<=11.5	11	69	36.157	0.107	51.779	30.005
8	11.5<x<=12.5	12	57	47.934	0.127	61.698	42.752
9	12.5<x<=13.5	13	43	56.818	0.135	65.521	56.290
10	13.5<x<=62.6	14	52	67.562	0.128	62.013	69.102
11	14.5<x<=15.5	15	55	78.926	0.108	52.308	79.910
12	15.5<x<=16.5	16	37	86.570	0.081	39.323	88.034
13	16.5<x<=17.5	17	27	92.149	0.054	26.346	93.478
14	17.5<x<=18.5	18	19	96.074	0.033	15.731	96.728
15	18.5<x<=19.5	19	10	98.140	0.017	8.372	98.458
16	19.5<x<=20.5	20	9	100.000	0.008	3.971	99.278
17	x>20.5	21	0	100.000	0.003	1.678	99.625
					No. of specimens		484
					Arthmetic mean		13.022
					Standard deviation		2.947
					1%LCL		6.156
					Skewness		0.281

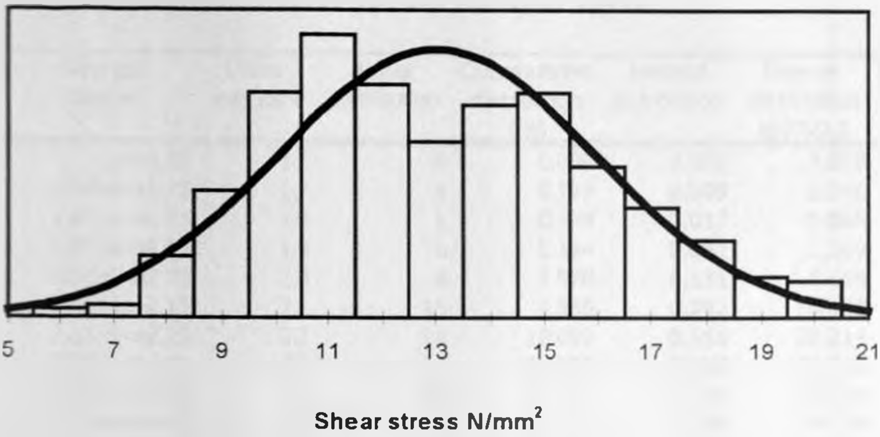

Figure 4.2.6-3 Trimmed Shear Histogram with Superimposed Normal

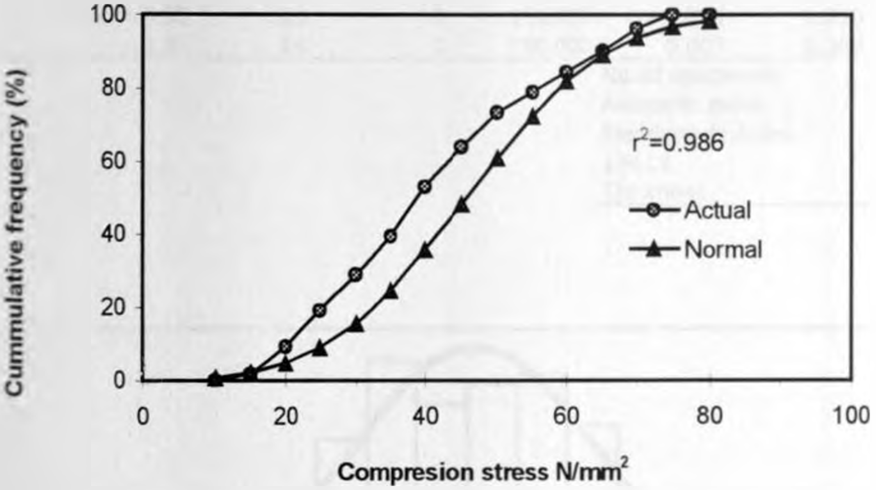

Figure 4.2.6-4 Trimmed Shear Cumulative Distribution Curves

Table 4.2.6-3 Transformed Shear Results Analysis Table

	Strength classes	Class midpoint	Actual distribution	Cummulative distribution (%)	Normal distribution	Normal distribution x507x0.1	Cummulative normal (%)
	x<=1.55	1.6	0	0.000	0.001	0.058	0
1	1.65<x<=1.75	1.7	1	0.197	0.005	0.240	0.047
2	1.75<x<=1.85	1.8	1	0.394	0.017	0.848	0.215
3	1.85<x<=1.95	1.9	0	0.394	0.051	2.569	0.721
4	1.95<x<=2.05	2.0	6	1.578	0.131	6.666	2.036
5	2.05<x<=2.15	2.1	15	4.536	0.292	14.818	4.959
6	2.15<x<=2.25	2.2	28	10.059	0.556	28.214	10.524
7	2.25<x<=2.35	2.3	53	20.513	0.908	46.018	19.600
8	2.35<x<=2.45	2.4	76	35.503	1.268	64.291	32.281
9	2.45<x<=2.55	2.5	63	47.929	1.518	76.939	47.456
10	2.55<x<=2.65	2.6	69	61.538	1.556	78.871	63.013
11	2.65<x<=2.75	2.7	72	75.740	1.366	69.257	76.673
12	2.75<x<=2.85	2.8	57	86.982	1.027	52.093	86.947
13	2.85<x<=2.95	2.9	31	93.097	0.662	33.563	93.567
14	2.95<x<=3.05	3.0	18	96.647	0.365	18.524	97.221
15	3.05<x<=3.05	3.1	12	99.014	0.173	8.757	98.948
16	3.15<x<=3.25	3.2	4	99.803	0.070	3.546	99.648
17	3.25<x<=3.35	3.3	1	100.000	0.024	1.230	99.890
18	x>3.45	3.4	0	100.000	0.007	0.366	99.962

No. of specimens	507
Arthmetic mean	2.566
Standard deviation	0.254
1%LCL	1.974
Skewness	0.054

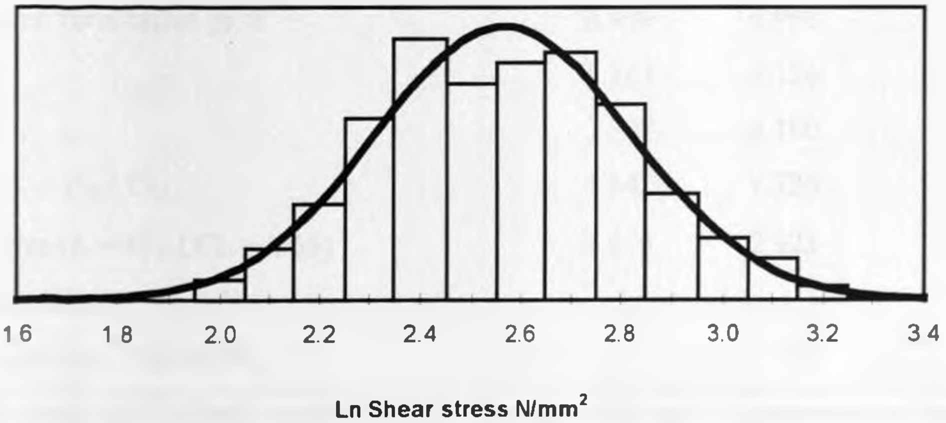

Figure 4.2.6-5 Transformed Shear Histogram with Superimposed Normal

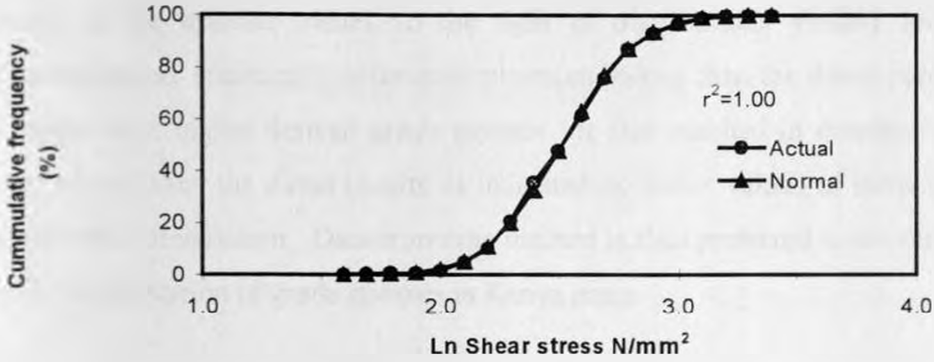

Figure 4.2.6-6 Transformed Shear Cumulative Distribution Curves

Table 4.2.6-4 Summary of Shear Parallel to Grains Test Results

Property	**Direct results**	**Trimmed data**	**Transformed data**
μ	13.442	13.022	13.014
σ	3.476	2.947	2.496
CV	25.9	22.6	19.2
skewness	0.728	0.281	0.054
r^2 between cumulative plots	0.998	0.998	1.0
1% LCL	5.343	6.156	7.198
5% LCL	7.707	8.160	8.556
5% LCL ÷ 1% LCL	1.442	1.326	1.189
Basic stress f_b = 1% LCL ÷ 2.65)	2.016	2.323	2.716
SS grade stress = f_b x 0.54	1.1	1.3	1.5
GS grade stress = f_b x0.54	1.1	1.3	1.5

1. The upper tail in direct results is not as distinct as the tail in compression parallel to grains direct results.
2. The r^2 values for direct, trimmed and transformed data indicate good correlation and almost unnoticeable difference in derived grade stresses.
3. The value of 1.189 for transformed data is closest to the BS 5268 value of 1.2

The following observations can be made from the summary tables and density plots:

1. Trimming of the extreme values to the right of distributions yielded lower averages but higher statistically estimated minimum values than the direct results and consequently, higher derived grade stresses. It also resulted in distributions closer to normal than the direct results as indicated by lower values of skewness and coefficients of variation. Data trimming method is thus preferred to the direct results in the derivation of grade stresses in Kenya pines.

2. Comparison between the three sets of results above shows that logarithmic transformation of data yields the best fit to normal distribution, as indicated by skewness values closest to zero, and lowest coefficients of variation. It also yields the highest statistically estimated minimum values and, thus, the highest basic and grade stresses.

3. The average ratio between the 5% and the 1% LCL values is 2.16 for the direct results, 1.82 for trimmed data and 1.25 for transformed data. BS 5268 gives a value of 1.2 for this ratio. The value for the transformed data compares very favourably with the BS 5268 values.

4. From the density versus strength relationships, the linear regression fits are seen to have a better representation than the logarithmic regression fits. The equations of the linear regression fits should thus be used as appropriate to describe the density versus strength relationships.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSIONS

The results of the research carried are in broad agreement with the findings of other researchers (Harley, Campbell). A practicable way of assessing the effects of compression wood was not established but by data transformation, the coefficients of variation were reduced and this gave better representation of the raw data and higher stresses. The following conclusions can be made:

i) A large scatter of test results especially in compression parallel to grains was observed and this confirms the high variability of Kenya pines.

ii) For all the strength properties, positive skewness of the test results was observed.

iii) Data trimming resulted in less scatter and skewness than the raw data analysis.

iv) Logarithmic data transformation resulted in the lowest scatter and skewness of the test results.

v) On comparison with the recommendations of BS 5268 of calculating 1% LCL values by reducing the 5% LCL values by a factor of 1.2 to bring them to the same broad level of safety, data transformation yielded the closest results.

vi) Logarithmic data transformation gives better results than statistical treatment of both direct and trimmed data for derivation of grade stresses in Kenya pines. Data transformation has been applied successfully in other disciplines that rely on statistical analysis as one way of dealing with the problem of excessive non-normality[17]. A summary of the recommended grade stresses as obtained through data transformation is given in appendix E.

5.2 RECOMMENDATIONS

The appropriateness of the following factors as used in this report need to be properly investigated through programmed and continuous testing on Kenyan pines:

(a) Effect of moisture content on strength. In the absence of further information, the increase factors from green to dry strength as given by Harley, and reproduced in appendix F should be used in design.
(b) Fibre saturation moisture content
(c) Load duration effect on the strength of timber
(d) Size effect on the strength of timber
(e) Safety factor
(f) Effect of shear deflection on modulus of elasticity

The structural timber industry in Kenya as it stands today is not very well developed. Presently, research in this industry is spearheaded by the Ministry of Roads and Public Works, although the government research body charged with this responsibility is the Kenya Forest Research Institute (KEFRI). When research has yielded sufficient data, it then becomes the work of the Kenya Bureau of Standards (KEBS), together with other players in the timber industry, to develop a new code or to revise the existing one. They may then invite personnel from MOPW and KEFRI and any other interested parties, such as the universities, to sit at the committees developing these codes. The new codes of practice become the property of KEBS who offer them for sale and enforce the minimum standards

Materials specified by the timber structural designer are not always readily available even when the local codes of practice and standards are used. Graded and treated timber is available from a few sawmills at exorbitant prices because the grading and treatment processes are expensive. Most of the timber available for structural use in the market is not graded since there is no statutory requirement compelling sawmills to sell graded timber. Most construction works in timber are still carried out in what has commonly come to be referred to as the "jua kali' industry where timber is likely to be selected without any regard to specification. The structural timber consumer in Kenya is not in any way protected from unscrupulous dealers who may offer substandard materials for sale. Minimum standards should therefore be set for timber as for any other goods on sale.

Provision of the missing information on Kenyan timbers alone is not enough to ensure the effective utilisation of locally available timbers. The following areas also need to be addressed properly in order to ensure the growth of the local timber industry and improve efficiency of usage of available timber.

i) Research
ii) Regulation of the industry
iii) Public sensitisation

5.2.1 RESEARCH

There should be more concerted efforts towards research in local timber. Most of the design parameters and expressions in timber engineering are empirical and since timber varies from place to place and across species, there is need to carry out the immense job of research on Kenya timbers. KEFRI together with contractors, consulting engineers and other research institutions in this field such as universities should be well equipped with modern facilities and finances to undertake this task. All concerned should also work hand in hand with each other where necessary. There should be collaboration with other international bodies in this area for information, new techniques and even funding. The persons directly involved in the research should be well remunerated to motivate them. The government through the KEBS should financially compensate the local bodies involved with the research so as to motivate and generate funds for further research.

5.2.2 REGULATION OF TIMBER INDUSTRY

Once KEBS obtains research findings, it should not only develop standards but should come up with measures to regulate the local timber industry. One such measure is to ensure that the saw millers and other dealers in structural timber offer material which meets certain minimum standards of grading only, and that such timbers are designated as "structural". Promotion of export trade in structural timber would also encourage the dealers to have their timber well graded and designated. These measures would protect the consumers from the risk of buying sub-standard timber that is unsuitable for structural purposes. This calls for more personnel who are well trained on timber grading and preservation.

5.2.3 Public Sensitization

There should be measures to sensitise the public on the importance of employing experts in their building and structural requirements. A large portion of the Kenyan population live in ignorance of the professionals in the building industry, with the result that they have to pay stiff penalties in terms of loss when structures collapse or become unfit for use during their design life. This ignorance has kept most people from using timber as a construction material, believing that such a structure is only temporary. If all those who aspire to build seek structural engineers' services, then the demand for graded timber would rise and the long-term effect would be a sure growth of the industry and increased afforestation.

REFERENCES

1. Baird J.A. and Ozelton E.C. (1995). *Timber Designer's Manual.* University Press Cambridge.
2. Bohannan W. (1966). *Effects of Size on Bending Strength of Wood Members.* US Forests Products Laboratory. Research paper no. FPL 56.
3. Booth L.G. and Reece P.O. (1967). *The Structural Use of Timber; A commentary on the British standard code for practice CP 112.* E.F. & Spon London.
4. BS 373: 1975, *The British Standard Specification for the Methods of Testing and Sampling of Small Clear Specimens.*
5. BS 4978: 1973, *The British Standard Specification for Softwood, Timber Grades for Structural Use.*
6. BS 5268: 1996 Part 2, *Code of Practice for the Structural Use of Timber; Permissible Design Stress, Materials and Workmanship.*
7. Campbell P.A. (1972). *Variability of the Strength Properties of the Kenya Pines.* Third East African Timber Symposium.
8. Carmichael E.N. (1967). *Timber Engineering Practical Design Studies.* E.F. & Spon London.
9. Dixon W.J. and Massey F.J. (1983). *Introduction to Statistical Analysis.* McGraw-Hill Inc. New York.
10. Freas A.D. and Selbo M.L. (1954). *Fabrication and Design of Glue-Laminated Wood Structural Members.* US Department of Agriculture Technical Bulletin No. 1069.
11. Harley G.K. (1993). *Updated Basic and Grade Stresses for Kenyan Grown Cypress and Pine.* (Unpublished Paper) MOPW Timber Engineering Seminar Nairobi.

12 Kothari C R (1993). *Research Methodology, Methods and Techniques.* Johri V S New Delhi

13 KS 02-771:1991, *The Kenyan standard specification for softwood; Timber grades for structural use.*

14 Mettem C.J (1986). *Structural Timber Design and Technology.* Longman London

15 Ministry of Environment and Natural Resources (1994) *Kenya Forestry Master Plan.* Nairobi

16 MOPW (1991). *Explanatory Notes on KS 02-771.* Nairobi (Unpublished Paper)

17 Norcliffe G.B (1977). *Inferential Statistics for Geographers.* Hutchinson, London

18 Ott R.L (1994). *Understanding Statistics.* Duxbury Press, Belmount

19 Patterson D.N.(1989). *Variation of Pinus Patula and its Application to Tree Breeding in East Africa.* University of East Africa (Ph D Thesis)

20 Pearson R.G., Kloot N.H and Boyd J.L (1962). *Timber Engineering Design Handbook.* Jacaranda Press, Brisbane Australia

21 Sunley J.G (1965). *Working Stresses for Structural Timbers.* Forest Products Research Bulletin no.47, 2nd edition HMSO. London

22 Timber Engineering Company (1965). *Timber Design and Construction Handbook* F.W Dodge Corporation. New York

23 Tsoumis G (1991). *Science and Technology of Wood.* Chapman & Hall, New York.

24 US Forest Products Laboratory (1964). *Wood Handbook.* USD Handbook No 72

25 Wood L. W (1960). *Relationship of Strength of Wood to Duration of Load.* US Forest Products Laboratory, Report No.1916

APPENDICES

Specimen No.	MOR N/mm^2	MOE x10^2 N/mm^2	LOP N/mm^2	Density g/cm^3	M.C (%)
1	79.363	94.57	65.265	0.512	12.60
2	26.093	33.99	17.743	0.279	13.39
3	94.789	120.00	71.873	0.567	12.66
4	57.283	54.55	34.685	0.420	12.31
5	123.095	155.66	76.546	0.612	13.58
6	49.282	47.94	38.388	0.401	14.55
7	67.589	82.33	34.056	0.463	12.62
8	44.140	40.14	28.904	0.346	12.83
9	61.579	83.38	39.662	0.421	13.00
10	92.912	117.27	65.038	0.526	12.74
11	94.225	139.27	62.126	0.477	12.92
12	41.475	35.02	25.725	0.334	12.27
13	62.469	99.74	59.866	0.488	12.27
14	48.124	76.97	33.118	0.375	12.50
15	46.146	62.36	38.369	0.396	12.48
16	59.103	88.45	56.464	0.596	12.33
17	33.068	36.01	22.734	0.349	13.33
18	50.888	75.74	33.752	0.417	14.10
19	62.325	80.74	47.008	0.414	12.95
20	59.714	65.95	45.038	0.398	13.06
21	69.030	91.67	49.455	0.419	12.25
22	58.391	68.89	44.315	0.361	12.48
23	81.737	96.51	59.207	0.422	12.52
24	95.121	118.33	72.770	0.489	12.59
25	44.746	55.05	33.819	0.325	12.04
26	40.991	47.84	27.853	0.294	12.48
27	48.300	65.33	42.000	0.409	11.83
28	43.267	48.34	31.659	0.334	12.35
29	50.024	63.04	33.870	0.369	12.63
30	39.179	51.07	31.343	0.299	12.88
31	60.175	68.41	39.425	0.372	13.33
32	67.471	81.55	51.382	0.436	13.41
33	54.819	51.22	35.317	0.380	12.23
34	42.921	44.62	33.499	0.324	12.15

of Bending Test Results

Specimen No.	MOR N/mm^2	MOE $x10^3 N/mm^2$	LOP N/mm^2	Density g/cm^3	M.C (%)
35	62.417	52.19	33.853	0.441	13.00
36	54.491	51.98	38.294	0.403	13.20
37	53.803	54.77	36.045	0.368	13.02
38	64.711	72.03	46.446	0.432	12.56
39	58.688	70.29	41.171	0.373	14.27
40	40.365	68.50	26.211	0.403	14.25
41	90.986	105.01	62.749	0.470	13.76
42	59.850	84.28	45.150	0.417	13.22
43	101.800	91.24	67.167	0.742	13.53
44	64.487	51.27	41.816	0.507	13.85
45	113.471	143.70	83.665	0.583	12.51
46	48.630	63.46	35.035	0.331	12.28
47	65.418	87.51	45.997	0.414	12.56
48	98.465	154.01	82.917	0.553	12.76
49	62.686	89.04	53.283	0.553	12.15
50	89.138	129.69	55.970	0.537	12.62
51	82.589	119.55	64.523	0.505	12.89
52	63.414	89.45	46.781	0.397	12.35
53	51.683	80.57	40.080	0.393	12.77
54	64.629	90.79	45.029	0.395	12.60
55	64.415	90.86	54.167	0.429	12.65
56	80.294	69.79	56.618	0.585	12.41
57	44.884	47.99	29.594	0.315	12.40
58	64.687	92.56	50.096	0.459	12.37
59	51.759	62.91	37.499	0.332	13.19
60	117.354	176.19	75.813	0.571	12.77
61	107.913	153.18	87.358	0.587	12.99
62	61.213	62.89	43.576	0.362	12.53
63	69.030	88.83	52.030	0.429	12.88
64	79.019	82.62	60.547	0.484	12.50
65	80.124	105.92	53.929	0.431	12.53
66	94.553	112.30	65.776	0.465	12.44
67	61.547	79.63	46.548	0.387	12.40
68	43.445	56.04	28.446	0.321	11.75

Specimen No.	MOR N/mm^2	MOE $x10^3 N/mm^2$	LOP N/mm^2	Density g/cm^3	M.C (%)
69	72.251	89.45	46.781	0.459	12.50
70	51.720	72.58	35.169	0.472	12.35
71	81.718	134.49	69.305	0.600	12.58
72	51.203	83.30	42.928	0.424	12.74
73	68.271	93.11	46.548	0.382	11.35
74	50.686	73.75	35.169	0.346	11.70
75	84.990	112.41	57.006	0.476	11.39
76	69.168	92.48	41.294	0.511	12.12
77	99.741	125.68	67.865	0.476	11.75
78	82.372	98.58	45.357	0.424	11.71
79	64.069	62.26	39.268	0.366	11.66
80	56.769	56.99	38.020	0.346	11.59
81	94.601	123.69	66.533	0.473	11.43
82	83.538	102.02	54.145	0.457	11.45
83	94.788	116.55	70.061	0.534	10.79
84	62.499	74.10	43.228	0.366	11.62
85	49.455	49.09	24.212	0.337	11.30
86	44.182	33.89	25.989	0.350	11.50
87	83.269	84.06	56.892	0.379	11.07
88	66.999	86.48	42.398	0.452	11.52
89	139.589	193.18	99.154	0.633	9.49
90	90.076	103.07	60.725	0.492	9.71
91	92.446	106.18	44.647	0.448	9.45
92	81.965	89.43	48.245	0.445	9.50
93	76.125	109.76	54.600	0.514	9.70
94	56.826	62.73	43.272	0.406	9.91
95	130.336	166.27	83.083	0.578	9.47
96	79.527	84.17	50.419	0.474	9.66
97	74.476	93.45	47.302	0.438	9.23
98	58.977	77.33	43.706	0.421	9.31
99	54.824	65.56	40.342	0.460	13.01
100	50.012	66.19	41.010	0.432	12.56
101	82.959	68.46	47.625	0.468	12.06
102	114.937	135.44	78.828	0.557	12.49

of Bending Test Results

Specimen No	MOR N/mm^2	MOE x10^2 N/mm^2	LOP N/mm^2	Density g/cm^3	M.C (%)
103	118.218	158.60	84.587	0.609	12.23
104	98.352	84.35	55.037	0.590	12.82
105	76.037	77.00	44.816	0.479	11.78
106	106.552	127.22	66.207	0.530	12.19
107	76.396	93.28	46.463	0.469	12.23
108	73.519	69.95	41.795	0.467	12.28
109	45.622	61.77	34.857	0.413	12.50
110	75.080	87.07	47.179	0.414	11.76
111	86.954	107.22	55.610	0.491	12.17
112	97.723	113.20	67.574	0.494	12.14
113	66.081	61.59	40.049	0.452	12.34
114	65.777	60.13	41.624	0.415	12.66
115	36.132	42.14	22.712	0.340	12.73
116	59.419	74.86	40.302	0.410	12.80
117	69.822	94.56	42.548	0.462	12.97
118	108.613	117.68	72.408	0.519	13.06
119	78.615	86.58	53.272	0.471	13.21
120	59.996	85.74	52.755	0.444	12.29
121	51.720	72.05	46.548	0.480	12.83
122	41.893	56.79	39.307	0.492	9.88
123	57.409	73.18	38.273	0.359	13.27
124	66.719	75.65	46.548	0.408	13.19
125	84.906	121.45	42.971	0.464	13.03
126	71.303	82.21	50.636	0.422	12.40
127	51.823	38.95	38.349	0.385	13.66
128	43.962	44.57	29.481	0.376	13.50
129	80.208	87.91	53.986	0.464	12.25
130	130.577	165.73	92.322	0.619	12.84
131	83.347	146.09	54.201	0.500	13.19
132	101.552	131.88	76.933	0.517	13.07
133	116.907	152.03	89.928	0.621	13.03
134	61.274	75.80	43.099	0.405	13.39
135	42.623	58.67	30.667	0.401	12.95
136	44.041	61.33	35.848	0.382	13.50

Specimen No	MOR N/mm^2	MOE $x10^2 N/mm^2$	LOP N/mm^2	Density g/cm^3	M.C (%)
137	78.098	123.28	56.892	0.480	13.38
138	76.318	120.29	59.301	0.483	12.90
139	60.727	73.96	42.200	0.461	13.37
140	68.447	59.95	40.657	0.526	14.23
141	115.793	126.26	87.488	0.581	14.47
142	47.440	33.49	25.783	0.414	14.07
143	124.376	156.98	92.130	0.677	13.92
144	115.854	150.42	87.925	0.607	14.30
145	91.288	105.69	75.902	0.618	14.35
146	120.190	160.54	93.654	0.600	13.98
147	85.685	101.61	50.069	0.474	14.59
148	91.970	96.72	62.519	0.513	14.43
149	60.063	64.23	42.609	0.419	13.88
150	68.304	81.17	42.431	0.495	14.55
151	72.998	83.92	48.406	0.463	14.42
152	93.561	108.55	71.730	0.582	13.67
153	69.305	102.93	49.134	0.546	14.50
154	72.998	68.68	51.771	0.506	14.72
155	103.854	132.38	69.236	0.561	14.59
156	106.530	151.76	77.195	0.585	14.12
157	106.437	141.82	78.536	0.604	14.27
158	117.922	163.02	82.752	0.633	14.24
159	56.667	69.07	31.939	0.401	11.88
160	57.354	79.34	34.310	0.438	11.97
161	79.254	117.91	58.154	0.519	12.06
162	37.239	47.90	26.895	0.286	12.04
163	151.279	189.29	97.105	0.724	12.17
164	155.634	179.45	95.677	0.781	12.30
165	155.971	145.42	67.305	0.581	12.11
166	72.049	96.04	47.347	0.452	12.22
167	79.768	116.00	57.269	0.475	11.98
168	86.204	117.45	59.008	0.513	11.95
169	67.530	92.87	37.346	0.467	11.95
170	59.462	80.94	39.983	0.427	12.24

Bending Test Results

Specimen No.	MOR N/mm^2	MOE x10^{2}N/mm^2	LOP N/mm^2	Density g/cm^3	M.C (%)
171	74.109	78.83	44.259	0.492	11.84
172	53.907	46.17	30.005	0.401	12.39
173	82.120	109.58	46.416	0.644	11.99
174	51.872	70.47	30.004	0.364	12.28
175	68.825	94.18	49.308	0.440	12.00
176	72.265	110.62	51.101	0.468	11.87
177	69.927	75.10	49.726	0.464	11.01
178	131.643	176.52	89.161	0.673	10.90
179	125.680	150.00	89.993	0.621	11.18
180	88.871	106.59	61.486	0.529	11.05
181	34.650	74.20	31.593	0.383	10.96
182	62.911	102.13	58.270	0.512	10.98
183	89.609	120.49	62.076	0.538	10.98
184	106.832	146.87	77.043	0.485	10.98
185	93.787	110.69	64.446	0.550	10.98
186	95.121	117.49	68.612	0.490	10.97
187	82.097	109.85	55.929	0.456	10.93
188	84.639	106.66	54.737	0.496	11.19
189	76.041	77.10	47.395	0.397	13.86
190	61.335	62.43	43.662	0.543	11.98
191	108.008	133.52	77.890	0.539	13.16
192	102.413	133.56	69.991	0.547	13.15
193	48.436	34.54	29.166	0.403	13.27
194	107.468	126.78	78.709	0.645	14.36
195	104.682	137.17	78.383	0.580	13.16
196	81.492	97.70	56.939	0.476	12.46
197	85.728	106.16	60.423	0.588	13.62
198	81.392	95.59	61.818	0.562	13.27
199	79.244	101.88	59.433	0.543	13.17
200	78.785	125.95	50.647	0.574	13.43
201	96.969	168.63	75.073	0.723	13.15
202	129.617	180.48	89.461	0.713	13.26
Mean	75.759	94.226	52.477	0.472	12.50
Std dev	25.271	35.451	17.834		

Appendix A1: Density versus Strength Plots-MOR

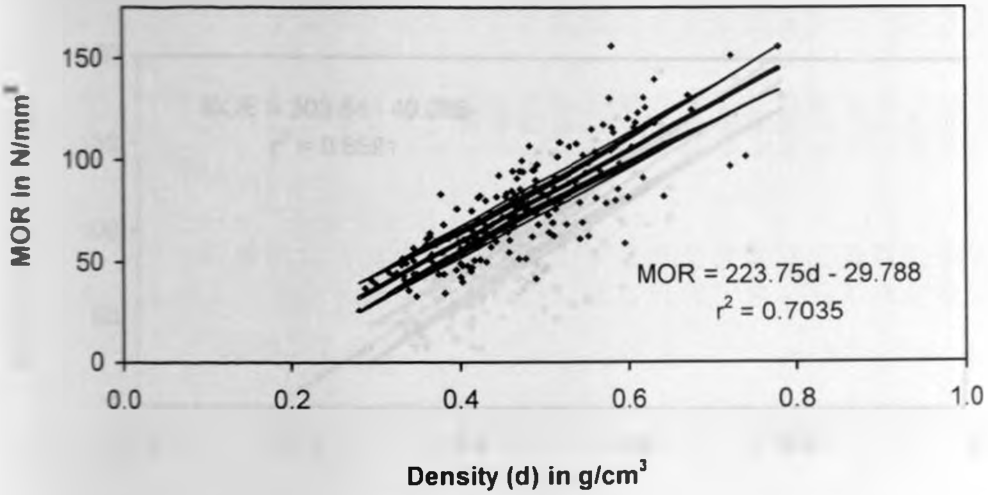

Figure A1.1 Plot of Density Vs MOR on Linear Scale

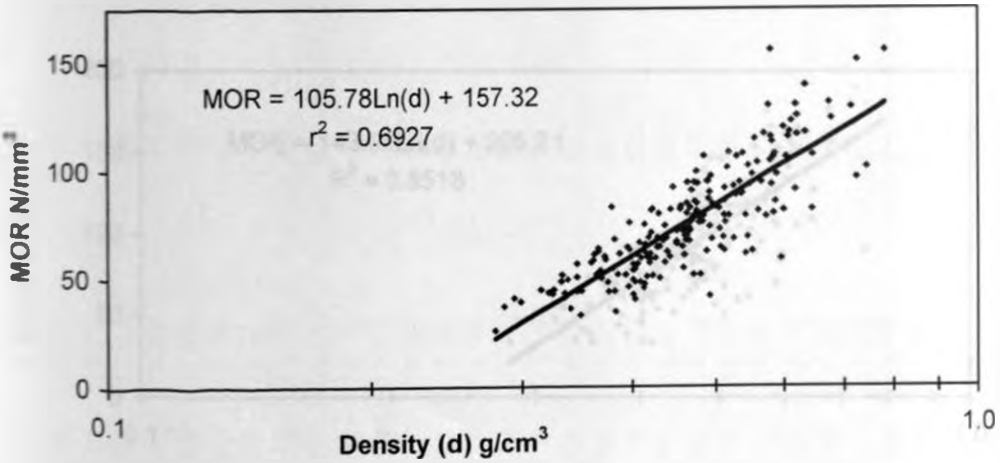

Figure A1.2 Density Vs MOR on Log-Normal Scale

Appendix A2: Density versus Strength Plots-MOE

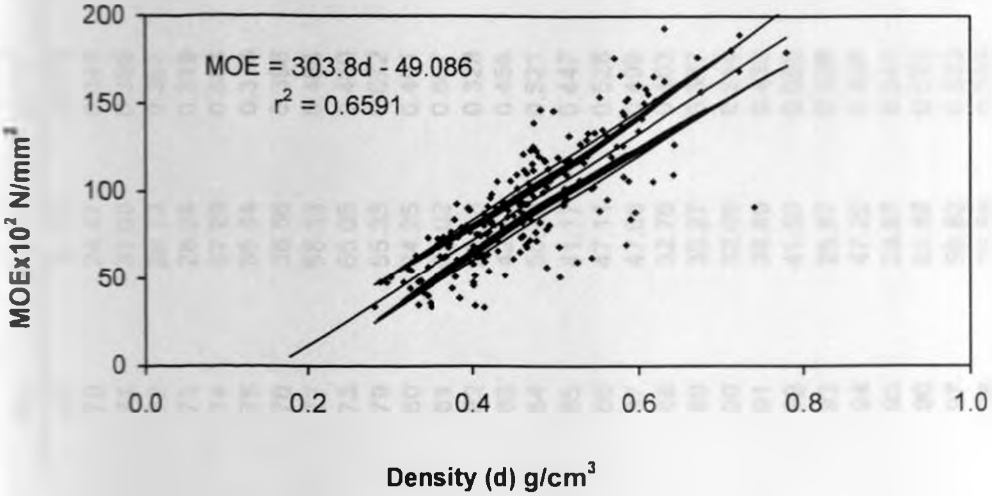

Figure A2.1 Plot of Density Vs MOE on Linear Scale

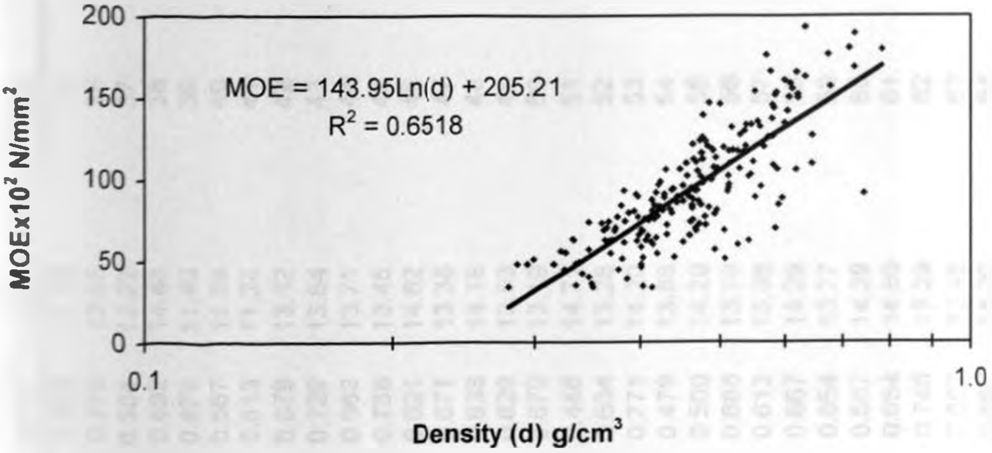

Figure A2.2 Density Vs MOE on Log-Normal Scale

Appendix B: Summary of Compression Parallel to Grains Test Results

Specimen No.	Comp stress N/mm^2	Density g/cm^3	M.C (%)
1	48.70	0.688	13.79
2	74.25	0.779	12.65
3	50.33	0.504	12.22
4	63.65	0.692	14.48
5	50.57	0.679	11.40
6	54.45	0.667	11.89
7	58.15	0.613	11.24
8	65.35	0.679	13.12
9	45.72	0.729	13.64
10	33.65	0.663	13.71
11	59.00	0.738	13.45
12	53.78	0.621	14.62
13	55.85	0.671	13.38
14	46.15	0.638	14.18
15	44.10	0.629	13.53
16	72.48	0.679	13.19
17	40.00	0.488	14.71
18	61.23	0.604	13.28
19	76.00	0.771	14.20
20	40.20	0.479	13.86
21	48.45	0.500	14.29
22	58.60	0.688	13.79
23	62.13	0.613	13.08
24	54.65	0.667	14.29
25	52.75	0.654	13.77
26	50.00	0.567	14.29
27	51.23	0.654	14.60
28	51.43	0.746	13.29
29	63.48	0.667	13.48
30	64.43	0.667	14.29
31	87.25	0.646	13.90
32	77.50	0.571	12.38
33	52.50	0.488	12.87
34	53.34	0.529	12.96
35	46.85	0.492	14.27
36	93.41	0.738	11.73
37	46.27	0.518	12.9
38	20.29	0.292	13.2
39	51.04	0.562	12.8
40	32.63	0.482	13.0
41	30.19	0.595	11.9
42	25.89	0.421	13.1
43	30.58	0.437	12.8
44	27.23	0.400	13.5
45	41.21	0.473	13.3
46	55.39	0.614	13.0
47	45.69	0.494	13.0
48	29.72	0.353	12.2
49	43.78	0.539	12.8
50	28.79	0.387	13.0
51	29.35	0.388	12.7
52	29.21	0.427	13.5
53	29.73	0.368	12.1
54	53.00	0.360	15.1
55	33.38	0.446	13.1
56	31.63	0.419	15.4
57	27.35	0.387	12.5
58	24.08	0.356	12.2
59	38.86	0.436	12.7
60	55.82	0.545	13.0
61	24.00	0.319	12.2
62	20.98	0.330	8.2
63	33.06	0.426	12.9
64	24.62	0.370	13.4
65	22.75	0.313	13.4
66	22.21	0.288	12.7
67	36.07	0.341	14.7
68	51.24	0.427	12.5
69	31.88	0.378	12.0
70	24.47	0.348	12.7
71	31.09	0.396	13.2
72	26.72	0.367	13.2
73	28.24	0.319	13.6
74	37.20	0.504	13.4
75	35.64	0.376	13.4
76	38.86	0.396	11.3
77	58.33	0.464	12.7
78	65.05	0.480	11.4
79	55.33	0.672	13.6
80	34.25	0.491	14.2
81	61.02	0.607	13.3
82	28.48	0.328	12.8
83	42.12	0.456	13.7
84	50.70	0.521	13.6
85	41.17	0.447	12.4
86	47.11	0.528	12.6
87	47.66	0.499	13.3
88	32.76	0.403	13.0
89	35.27	0.387	12.8
90	32.09	0.344	13.0
91	38.89	0.433	12.7
92	41.50	0.555	14.1
93	25.87	0.326	12.9
94	47.26	0.495	12.7
95	28.87	0.340	13.5
96	61.87	0.571	13.2
97	50.82	0.523	13.9
98	29.89	0.363	13.4
99	37.35	0.438	13.9
100	40.37	0.469	14.1
101	42.95	0.423	13.7
102	50.27	0.480	13.6

[illegible] Parallel to Grains Test Results

Specimen No.	Comp stress N/mm^2	Density g/cm^3	M.C (%)
103	34.24	0.399	13.7
104	26.63	0.329	13.2
105	42.57	0.466	13.6
106	33.55	0.464	14.5
107	55.75	0.601	13.4
108	36.95	0.424	13.8
109	38.37	0.389	13.3
110	31.53	0.344	13.3
111	47.28	0.509	11.2
112	42.08	0.507	11.7
113	63.98	0.498	11.3
114	43.43	0.446	11.4
115	28.59	0.342	11.4
116	26.12	0.325	11.2
117	52.97	0.489	11.3
118	44.93	0.467	11.7
119	46.41	0.477	11.2
120	53.73	0.521	11.7
121	24.26	0.344	11.7
122	24.50	0.361	11.4
123	35.02	0.399	11.1
124	43.32	0.447	11.4
125	76.73	0.618	9.7
126	39.91	0.420	9.7
127	49.92	0.490	9.5
128	47.58	0.444	9.2
129	53.10	0.530	10.0
130	32.43	0.409	9.6
131	67.82	0.570	9.6
132	42.91	0.461	9.8
133	42.08	0.416	9.8
134	41.63	0.427	9.6
135	27.65	0.461	13.1
136	38.57	0.493	12.7
137	23.96	0.367	12.5
138	49.14	0.516	12.5
139	52.26	0.568	11.8
140	45.87	0.620	12.6
141	34.26	0.485	11.5
142	46.94	0.541	11.8
143	48.01	0.505	11.9
144	34.24	0.444	12.2
145	29.69	0.394	12.3
146	26.11	0.385	11.3
147	44.93	0.512	12.0
148	50.86	0.552	12.0
149	34.96	0.442	12.5
150	35.19	0.434	12.5
151	20.24	0.333	12.5
152	36.14	0.383	12.4
153	45.79	0.469	12.7
154	51.36	0.537	13.0
155	49.01	0.526	13.1
156	41.62	0.450	12.4
157	38.33	0.468	12.6
158	32.39	0.433	12.2
159	27.60	0.366	12.8
160	37.38	0.409	12.8
161	44.55	0.452	12.6
162	40.09	0.455	13.0
163	29.32	0.375	13.3
164	32.43	0.441	13.4
165	34.85	0.439	12.9
166	62.62	0.597	13.2
167	59.40	0.557	13.2
168	58.86	0.536	13.5
169	48.51	0.503	13.2
170	38.86	0.464	13.1
171	27.48	0.417	13.0
172	25.25	0.373	13.2
173	47.29	0.500	13.4
174	42.61	0.445	13.0
175	37.09	0.456	13.4
176	40.15	0.577	14.3
177	65.59	0.617	14.6
178	23.51	0.433	14.2
179	71.57	0.683	14.1
180	60.04	0.593	15.0
181	62.43	0.613	14.3
182	56.37	0.595	15.0
183	44.53	0.484	14.8
184	31.03	0.421	14.6
185	21.77	0.390	14.3
186	32.84	0.438	14.8
187	33.70	0.439	15.2
188	58.82	0.553	13.9
189	53.86	0.574	12.4
190	42.08	0.538	10.1
191	54.53	0.571	14.9
192	54.16	0.571	14.5
193	71.25	0.644	16.3
194	65.56	0.635	12.7
195	33.54	0.390	12.8
196	35.78	0.434	12.9
197	51.78	0.518	12.8
198	22.76	0.270	12.9
199	80.14	0.689	12.9
200	92.39	0.748	13.1
201	77.52	0.664	12.6
202	46.08	0.463	12.7
203	44.58	0.456	12.7
204	54.81	0.561	13.5

Specimen No.	Comp stress N/mm²	Density g/cm³	M.C (%)
205	39.32	0.474	12.6
206	29.96	0.389	12.6
207	45.65	0.501	12.3
208	31.25	0.366	13.0
209	52.57	0.578	12.7
210	27.11	0.377	12.5
211	44.20	0.448	12.5
212	44.73	0.494	12.4
213	47.08	0.507	12.6
214	58.75	0.628	12.7
215	64.60	0.608	13.0
216	46.53	0.533	12.5
217	28.58	0.390	12.6
218	47.02	0.542	12.8
219	41.07	0.415	12.7
220	43.49	0.447	12.8
221	51.50	0.541	13.1
222	43.34	0.465	13.0
223	50.49	0.530	12.9
224	55.75	0.588	12.6
225	47.64	0.552	13.8
226	33.54	0.430	12.3
227	56.72	0.564	13.3
228	53.13	0.558	13.1
229	72.99	0.701	13.3
230	32.34	0.424	12.8
231	51.58	0.554	13.4
232	41.79	0.464	12.9
233	43.73	0.575	13.6
234	39.85	0.516	13.5
235	45.40	0.535	13.4
236	47.06	0.572	13.1
237	72.89	0.716	13.1
238	81.34	0.733	12.9
239	86.20	0.625	12.6
240	74.55	0.633	11.1
241	83.45	0.733	12.4
242	70.43	0.700	13.3
243	71.19	0.708	11.9
244	40.66	0.575	12.4
245	49.25	0.442	13 0
246	72.82	0.608	12.0
247	72.46	0.521	13.8
248	47.85	0.483	12.5
249	72.84	0.654	12.4
250	62.93	0.593	12.7
251	63.06	0.583	13.7
252	73.05	0.692	12.1
253	69.62	0.658	11.6
254	41.50	0.704	13.3
255	52.65	0.525	11.1
256	69.40	0.579	12.3
257	70.48	0.563	11.7
258	62.31	0.546	11.8
259	72.48	0.450	16.1
260	75.36	0.463	12.7
261	27.42	0.458	14.8
262	70.54	0.208	12.0
263	41.08	0.525	12.6
264	50.17	0.621	12.8
265	74.63	0.671	13.6
266	41.02	0.454	12.4
267	75.90	0.604	12.1
268	80.64	0.725	12.5
269	50.32	0.400	13.4
270	72.57	0.583	11.5
271	67.66	0.575	12.3
272	55.09	0.475	12.6
273	46.56	0.554	12.7
274	72.11	0.583	12.7
275	64.72	0.513	12.1
276	55.22	0.454	13.1
277	34.14	0.279	13.5
278	76.03	0.504	13.1
279	74.50	0.592	13.0
280	63.51	0.596	13.4
281	86.56	0.588	13.8
282	67.08	0.279	15.1
283	79.72	0.604	11.3
284	79.43	0.692	13.4
285	65.70	0.575	13.6
286	83.51	0.488	13.4
287	78.17	0.613	13.41
288	72.32	0.579	12.3
289	46.40	0.329	12.3
290	53.34	0.650	13.8
291	78.82	0.696	12.0
292	55.84	0.542	14.4
293	57.63	0.538	12.7
294	41.14	0.567	13.9
295	49.46	0.271	12.6
296	74.05	0.700	12.7
297	77.61	0.604	12.1
298	79.66	0.625	13.4
299	79.78	0.588	13.0
300	90.07	0.792	13.0
301	70.42	0.300	13.4
302	71.88	0.683	12.8
Mean	49.086	0.510	12.86
Std dev	16.684		

Appendix B1: Density versus Strength Plots-Compression Stress

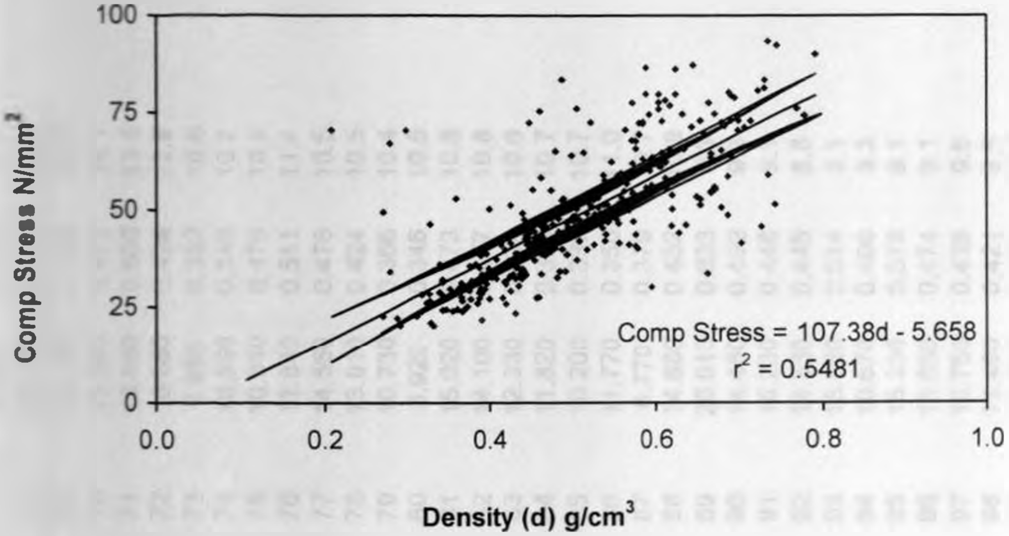

Figure B1.1 Plot of Density Vs Compression Stress on Linear Scale

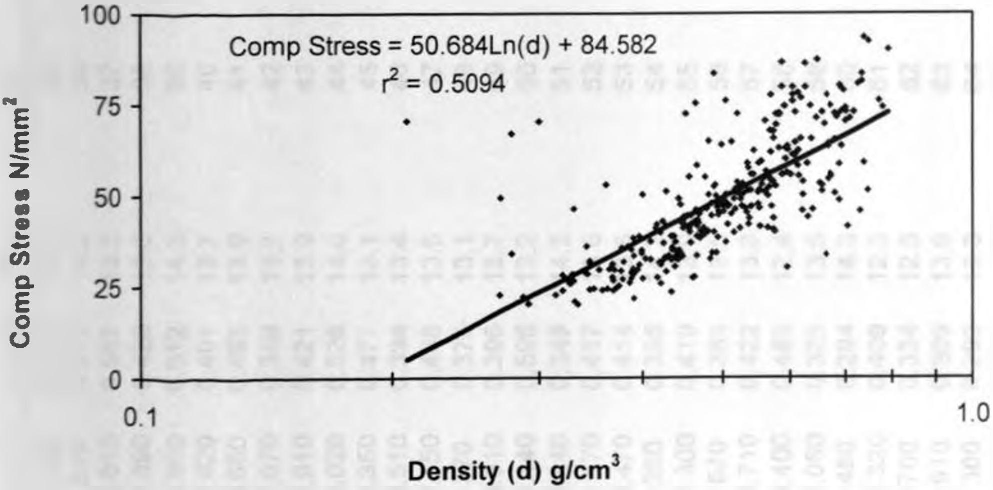

Figure B1.2 Density Vs Compression Stress on Log-Normal Scale

Appendix C: Summary of Shear Parallel to Grains Test Results

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
1	15.380	0.512	13.1
2	8.510	0.279	14.2
3	15.810	0.567	13.3
4	15.890	0.420	13.6
5	17.500	0.612	14.3
6	12.920	0.401	13.7
7	13.650	0.463	13.9
8	11.070	0.346	13.7
9	11.910	0.421	13.9
10	15.020	0.526	14.0
11	15.350	0.477	13.1
12	10.510	0.334	13.4
13	11.750	0.488	13.5
14	9.370	0.375	13.1
15	10.910	0.396	13.7
16	12.140	0.596	13.2
17	12.840	0.349	14.3
18	11.170	0.417	13.6
19	10.470	0.414	13.6
20	9.260	0.398	14.2
21	11.300	0.419	13.0
22	9.870	0.361	13.5
23	14.710	0.422	13.3
24	14.400	0.489	12.4
25	10.080	0.325	13.5
26	8.480	0.294	14.3
27	10.320	0.409	12.3
28	9.700	0.334	12.5
29	7.910	0.369	13.9
30	8.300	0.299	13.3
31	11.740	0.372	12.8
32	14.150	0.436	13.5
33	12.430	0.380	14.0
34	10.040	0.324	13.5
35	10.970	0.441	12.9
36	11.310	0.403	13.8
37	8.400	0.368	13.7
38	10.780	0.432	12.9
39	10.800	0.373	13.4
40	9.300	0.403	14.1
41	15.400	0.470	13.7
42	12.740	0.417	14.0
43	20.100	0.742	13.9
44	11.090	0.507	13.9
45	19.260	0.583	13.1
46	7.700	0.331	13.1
47	9.990	0.414	13.5
48	10.370	0.553	13.2
49	11.080	0.553	12.4
50	15.970	0.537	12.8
51	13.060	0.505	13.6
52	10.360	0.397	13.5
53	10.390	0.393	13.6
54	8.860	0.395	13.3
55	13.100	0.429	12.8
56	15.590	0.585	14.4
57	9.000	0.315	13.2
58	9.110	0.459	12.7
59	10.380	0.332	13.9
60	9.230	0.571	13.3
61	15.960	0.587	13.6
62	9.750	0.362	12.9
63	12.870	0.429	14.1
64	15.320	0.484	14.2
65	11.630	0.431	13.5
66	12.470	0.465	13.0
67	9.600	0.387	13.7
68	10.370	0.321	13.0
69	13.180	0.459	13.4
70	13.560	0.472	14.1
71	13.890	0.600	13.3
72	10.080	0.424	12.8
73	9.950	0.382	10.6
74	10.590	0.346	10.7
75	10.340	0.476	10.9
76	11.840	0.511	11.4
77	14.560	0.476	10.5
78	13.910	0.424	10.5
79	10.730	0.366	10.4
80	8.920	0.346	10.5
81	15.020	0.473	10.8
82	14.100	0.457	10.8
83	12.330	0.534	10.6
84	11.820	0.366	10.7
85	10.200	0.337	10.7
86	11.770	0.350	11.0
87	8.770	0.379	10.7
88	14.680	0.452	10.9
89	20.010	0.633	9.3
90	14.450	0.492	9.3
91	16.230	0.448	9.1
92	14.530	0.445	8.8
93	16.830	0.514	9.1
94	10.670	0.406	9.3
95	15.330	0.578	9.1
96	15.650	0.474	9.1
97	16.750	0.438	9.6
98	13.490	0.421	9.5
99	14.730	0.460	11.8
100	16.200	0.432	11.8
101	10.060	0.468	11.5
102	15.300	0.557	11.8

Appendix C: Summary of Shear Parallel to Grains Test Results

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
103	20.420	0.609	11.1
104	20.470	0.590	11.8
105	12.550	0.479	12.3
106	19.020	0.530	11.4
107	15.360	0.469	11.5
108	11.720	0.467	11.5
109	12.020	0.413	11.3
110	11.410	0.414	10.9
111	17.270	0.491	11.4
112	17.500	0.494	11.4
113	14.480	0.452	11.8
114	14.570	0.415	11.8
115	11.580	0.340	12.7
116	8.930	0.410	12.2
117	11.600	0.462	12.6
118	18.810	0.519	12.9
119	16.190	0.471	12.8
120	9.430	0.444	12.2
121	15.360	0.480	12.3
122	10.360	0.492	12.0
123	9.710	0.359	12.7
124	10.080	0.408	12.7
125	14.000	0.464	12.6
126	13.140	0.422	11.7
127	10.170	0.385	13.2
128	14.120	0.376	13.3
129	12.220	0.464	12.1
130	16.790	0.619	14.1
131	12.360	0.500	12.6
132	8.120	0.517	12.7
133	13.750	0.621	12.2
134	12.770	0.405	12.2
135	10.070	0.401	12.9
136	10.950	0.382	12.5
137	11.840	0.480	12.6
138	12.380	0.483	12.6
139	11.040	0.461	12.8
140	15.350	0.526	13.6
141	16.440	0.581	13.9
142	9.310	0.414	13.6
143	12.140	0.677	13.4
144	17.860	0.607	13.9
145	16.240	0.618	13.3
146	16.410	0.600	13.6
147	13.530	0.474	13.7
148	11.310	0.513	13.7
149	10.330	0.419	13.3
150	13.680	0.495	13.5
151	11.520	0.463	14.3
152	13.830	0.582	13.2
153	15.500	0.546	13.5
154	12.760	0.506	14.0
155	14.960	0.561	13.6
156	16.160	0.585	13.5
157	16.400	0.604	13.7
158	15.820	0.633	13.6
159	12.050	0.401	12.7
160	13.890	0.438	12.7
161	16.300	0.519	13.0
162	8.380	0.286	12.9
163	12.000	0.724	13.4
164	17.050	0.781	13.4
165	18.140	0.581	13.3
166	15.200	0.452	13.5
167	8.350	0.475	13.1
168	13.070	0.513	13.7
169	10.630	0.467	13.2
170	9.770	0.427	12.7
171	13.920	0.492	12.3
172	10.700	0.401	13.3
173	10.780	0.644	12.9
174	11.590	0.364	12.7
175	11.170	0.440	13.4
176	15.590	0.468	12.8
177	14.780	0.464	12.6
178	15.460	0.673	12.4
179	12.330	0.621	12.5
180	14.160	0.529	12.6
181	13.530	0.383	12.6
182	11.340	0.512	12.6
183	11.080	0.538	12.4
184	11.430	0.485	12.6
185	18.210	0.550	12.9
186	13.730	0.490	12.5
187	11.390	0.456	12.4
188	14.010	0.496	12.2
189	15.790	0.397	13.6
190	11.880	0.543	12.3
191	15.780	0.539	12.6
192	16.060	0.547	12.3
193	18.470	0.403	13.0
194	11.350	0.645	12.1
195	14.500	0.580	12.7
196	11.590	0.476	12.2
197	15.150	0.588	13.1
198	15.320	0.562	12.7
199	14.670	0.543	12.9
200	15.760	0.574	12.9
201	20.040	0.723	12.6
202	22.290	0.713	11.8
203	13.175	0.375	11.9
204	12.750	0.413	12.6

Appendix C : Summary of Shear Parallel to Grains Test Results

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
205	10.600	0.438	12.4
206	12.625	0.388	13.0
207	11.525	0.338	12.9
208	9.825	0.331	13.7
209	10.575	0.294	12.3
210	8.625	0.269	12.7
211	8.625	0.309	12.5
212	10.575	0.330	12.4
213	22.075	0.381	12.6
214	18.600	0.388	12.6
215	9.850	0.375	12.2
216	15.775	0.600	12.1
217	14.020	0.478	13.6
218	16.577	0.440	12.0
219	12.067	0.388	11.6
220	16.415	0.498	12.8
221	20.344	0.531	11.9
222	17.670	0.463	12.6
223	15.043	0.625	13.4
224	9.765	0.369	14.2
225	11.230	0.343	13.6
226	14.369	0.361	13.2
227	10.951	0.413	13.6
228	11.439	0.323	13.1
229	11.462	0.319	13.2
230	12.741	0.400	14.5
231	11.486	0.348	14.6
232	10.881	0.348	14.0
233	12.927	0.374	14.1
234	14.020	0.424	12.9
235	16.089	0.523	13.0
236	17.275	0.524	13.3
237	15.833	0.469	12.8
238	11.021	0.479	13.7

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
239	19.856	0.549	13.8
240	9.858	0.378	12.6
241	16.694	0.506	12.8
242	25.157	0.663	13.2
243	18.109	0.665	13.4
244	23.948	0.635	13.4
245	15.415	0.573	12.7
246	15.252	0.569	12.9
247	16.717	0.535	13.5
248	17.252	0.678	13.9
249	21.204	0.650	13.8
250	16.973	0.639	13.9
251	5.696	0.506	13.0
252	13.346	0.408	13.0
253	10.525	0.463	12.6
254	10.825	0.363	13.8
255	12.575	0.450	14.2
256	8.250	0.394	13.4
257	11.725	0.400	11.4
258	11.525	0.350	12.0
259	10.525	0.354	11.7
260	10.650	0.363	11.4
261	10.250	0.351	12.1
262	15.150	0.390	13.7
263	10.700	0.399	13.0
264	14.050	0.406	12.9
265	13.950	0.438	13.7
266	13.775	0.336	13.4
267	13.225	0.393	13.3
268	12.075	0.344	13.0
269	10.850	0.375	13.8
270	13.350	0.375	12.9
271	16.750	0.463	13.0
272	19.300	0.463	12.8

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
273	12.450	0.439	12.3
274	14.575	0.414	14.0
275	12.050	0.386	13.7
276	13.725	0.391	13.5
277	14.575	0.413	12.8
278	13.525	0.388	13.1
279	10.500	0.315	12.8
280	10.275	0.388	12.7
281	17.675	0.456	12.2
282	13.125	0.476	11.9
283	12.600	0.353	12.8
284	10.675	0.363	12.6
285	11.175	0.363	12.4
286	14.125	0.350	12.8
287	15.875	0.485	12.0
288	10.900	0.365	12.1
289	13.500	0.390	13.5
290	11.600	0.413	12.8
291	11.700	0.408	13.3
292	9.250	0.349	13.4
293	12.850	0.338	12.9
294	11.900	0.304	13.0
295	14.775	0.434	12.9
296	10.675	0.386	12.7
297	22.000	0.625	12.6
298	17.075	0.561	12.7
299	21.325	0.588	11.9
300	19.375	0.538	12.7
301	16.625	0.544	12.6
302	12.125	0.375	12.4
303	10.175	0.360	13.4
304	15.225	0.425	12.9
305	19.600	0.688	12.7
306	16.725	0.631	13.5

Appendix C: Summary of Shear Parallel to Grains Test Results

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
307	13.375	0.394	13.3
308	14.875	0.456	13.4
309	16.350	0.603	13.6
310	11.925	0.463	13.7
311	15.650	0.394	13.8
312	16.825	0.469	12.8
313	16.450	0.436	13.7
314	11.950	0.375	12.7
315	13.725	0.378	12.8
316	13.300	0.403	13.4
317	9.025	0.306	11.9
318	14.475	0.481	12.6
319	10.875	0.339	11.8
320	14.550	0.410	12.1
321	14.775	0.441	13.1
322	16.500	0.415	12.6
323	18.175	0.475	11.7
324	15.000	0.459	12.3
325	12.850	0.415	13.3
326	13.825	0.403	13.3
327	8.925	0.373	12.6
328	14.150	0.400	12.6
329	18.150	0.856	12.1
330	20.575	0.749	12.1
331	22.000	0.675	13.2
332	20.800	0.631	13.2
333	24.575	0.650	13.0
334	25.900	0.708	13.0
335	14.525	0.394	14.4
336	15.300	0.436	14.4
337	9.975	0.440	14.4
338	11.550	0.341	12.6
339	12.275	0.316	12.6
340	10.775	0.338	12.6
341	10.325	0.325	14.0
342	9.725	0.356	14.6
343	19.575	0.538	12.0
344	10.275	0.500	14.3
345	10.050	0.438	14.6
346	12.025	0.540	13.0
347	15.675	0.466	12.6
348	12.675	0.463	12.4
349	10.675	0.489	12.8
350	14.025	0.344	12.7
351	10.450	0.344	11.5
352	13.425	0.363	12.2
353	15.100	0.465	11.8
354	9.350	0.336	11.6
355	10.300	0.313	12.6
356	12.200	0.380	13.0
357	16.900	0.600	13.0
358	15.975	0.463	13.2
359	15.250	0.464	12.9
360	11.100	0.311	13.0
361	11.625	0.324	12.4
362	11.741	0.328	12.7
363	14.415	0.348	13.4
364	10.486	0.350	13.0
365	8.789	0.376	13.6
366	13.415	0.383	12.4
367	10.160	0.389	13.1
368	11.067	0.425	14.7
369	8.138	0.343	13.6
370	13.578	0.351	13.8
371	8.789	0.320	12.1
372	14.438	0.476	12.4
373	10.393	0.328	13.2
374	13.346	0.378	12.5
375	11.393	0.353	13.5
376	8.742	0.288	13.9
377	10.416	0.350	13.5
378	11.090	0.358	14.8
379	8.928	0.325	14.2
380	11.346	0.425	13.9
381	15.136	0.419	12.8
382	9.509	0.348	13.5
383	9.835	0.375	13.6
384	15.206	0.469	12.5
385	20.693	0.615	10.8
386	21.948	0.594	11.1
387	22.204	0.594	12.0
388	23.041	0.598	11.6
389	16.508	0.540	12.8
390	20.437	0.588	12.2
391	22.785	0.574	10.9
392	7.766	0.331	13.0
393	13.508	0.375	12.7
394	14.392	0.500	12.9
395	18.205	0.565	13.1
396	12.602	0.445	13.2
397	18.251	0.451	13.4
398	16.252	0.525	12.1
399	17.763	0.538	12.3
400	14.601	0.544	12.3
401	14.601	0.544	11.7
402	19.925	0.600	12.5
403	13.834	0.575	12.3
404	17.763	0.538	12.2
405	9.649	0.363	12.5
406	12.974	0.450	12.3
407	12.276	0.353	12.5
408	13.206	0.410	12.5

Specimen No.	Shear N/mm2	Density g/cm3	M.C (%)
409	12.020	0.375	12.4
410	10.811	0.451	12.3
411	15.717	0.400	12.3
412	10.253	0.313	12.2
413	11.207	0.321	12.1
414	8.510	0.300	12.2
415	15.113	0.325	11.8
416	13.671	0.350	11.9
417	8.510	0.300	12.0
418	14.299	0.438	12.1
419	15.857	0.438	12.2
420	15.113	0.451	12.3
421	9.300	0.338	13.2
422	10.579	0.503	12.2
423	15.043	0.449	12.4
424	18.507	0.556	12.7
425	12.881	0.505	12.5
426	14.276	0.436	12.7
427	11.834	0.428	13.2
428	18.437	0.528	12.8
429	15.113	0.521	13.0
430	11.602	0.405	12.8
431	15.694	0.444	14.0
432	13.113	0.509	13.8
433	10.718	0.388	13.6
434	8.719	0.385	13.4
435	13.415	0.420	13.7
436	14.183	0.439	13.8
437	10.997	0.443	11.7
438	8.370	0.450	12.8
439	10.044	0.475	11.9
440	12.020	0.538	12.1
441	10.625	0.563	12.2
442	8.370	0.450	12.4
443	5.813	0.513	12.6
444	11.346	0.363	11.0
445	10.742	0.350	13.8
446	11.811	0.350	13.3
447	14.578	0.463	13.8
448	11.346	0.363	13.6
449	11.811	0.363	13.7
450	14.159	0.413	13.8
451	17.879	0.463	12.6
452	11.207	0.506	13.7
453	10.742	0.451	12.8
454	14.996	0.500	13.5
455	17.159	0.513	13.6
456	14.229	0.500	13.0
457	17.879	0.463	12.9
458	17.298	0.475	12.6
459	16.577	0.488	13.7
460	17.298	0.475	13.6
461	17.345	0.463	13.6
462	14.508	0.425	13.4
463	12.485	0.400	13.7
464	16.577	0.488	13.6
465	9.323	0.311	13.0
466	10.253	0.301	12.8
467	9.323	0.328	12.9
468	9.881	0.321	13.1
469	10.067	0.338	13.1
470	8.161	0.313	12.9
471	7.324	0.288	13.5
472	7.301	0.313	13.6
473	7.580	0.300	14.1
474	9.230	0.325	13.9
475	7.324	0.288	13.8
476	13.625	0.490	12.4
477	12.253	0.451	14.7
478	13.834	0.511	14.5
479	14.020	0.448	12.7
480	14.624	0.496	11.8
481	12.927	0.449	12.7
482	13.369	0.425	12.3
483	10.463	0.425	11.9
484	11.974	0.481	11.6
485	12.299	0.475	12.1
486	16.601	0.525	11.9
487	14.508	0.525	12.0
488	21.716	0.564	12.2
489	10.997	0.390	12.4
490	15.740	0.504	12.6
491	13.625	0.463	12.7
492	9.812	0.383	13.1
493	18.554	0.563	13.1
494	18.205	0.578	12.9
495	23.436	0.636	13.0
496	18.182	0.590	12.9
497	19.925	0.588	12.8
498	18.926	0.613	13.3
499	15.159	0.490	13.1
500	18.972	0.563	13.0
501	13.299	0.478	13.3
502	23.297	0.654	13.0
503	18.461	0.525	12.8
504	13.043	0.438	12.9
505	8.789	0.338	14.9
506	11.393	0.344	12.6
507	11.230	0.318	12.4
Mean	13.442	0.457	12.83
Std dev	3.476		

Appendix C1: Density versus Strength Plots-Shear Stress

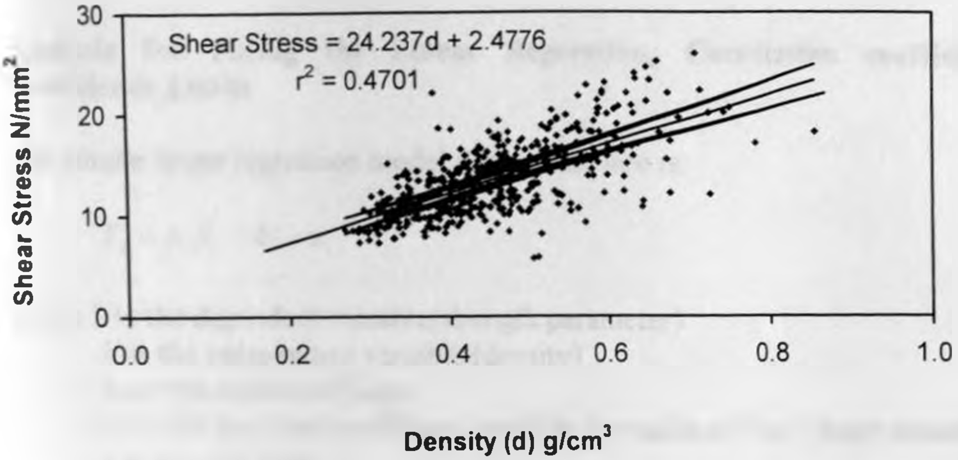

Figure C1.1 Plot of Density Vs Shear Stress on Linear Scale

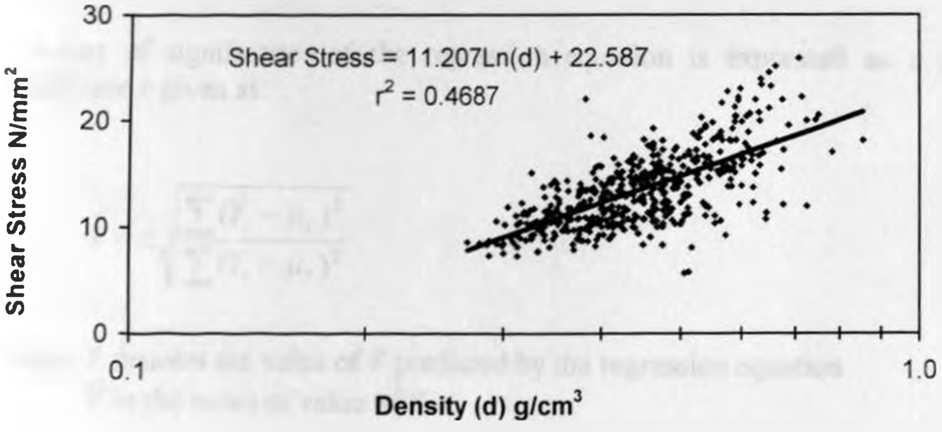

Figure C1.2 Density Vs Shear Stress on Log-Normal Scale

APPENDIX D

Analysis for Fitting the Linear Regression, Correlation coefficients and Confidence Limits

The simple linear regression model considered here is:

$$Y_i = b_0 X_i + b_1 + e_i$$

where Y is the dependent variable(strength parameter)
X is the independent variable (density)
b_0 is the slope coefficient
b_1 is the intercept coefficient, equal to the value of Y at a point where X = 0.
e is an error term.

The coefficients b_0 and b_1 are estimated using these squares as:

$$b_1 = \frac{(\Sigma Y_i)(\Sigma X_i^2) - (\Sigma X_i)(\Sigma X_i Y_i)}{N \Sigma X_i^2 - (\Sigma X_i)^2}$$

$$b_0 = \frac{N \Sigma X_i Y_i - \Sigma X_i)(\Sigma Y_i)}{N \Sigma X_i^2 - (\Sigma X_i)^2}$$

The test of significance of the regression equation is expressed as a correlation coefficient r given as:

$$r = \pm \sqrt{\frac{\sum (\hat{Y}_i - \mu_Y)^2}{\sum (Y_i - \mu_Y)^2}}$$

Where $\hat{Y}$ denotes the value of Y predicted by the regression equation.
$\bar{Y}$ is the mean of value of Y.

The variance of Y given the effect of X (i.e. the variance of the residuals about the regression line) is obtained as:

$$\hat{s}_{Y.X}^2 = \frac{(\Sigma \hat{Y}_i - \bar{Y})^2}{N-2} = \frac{\Sigma e_i^2}{N-2}$$

APPENDIX D Continued...

The standard error of the regression line corresponding to any value of X is defined as:

$$\hat{sY} = \hat{s}^2_{Y.X}\sqrt{\left\{\frac{1}{N}+\frac{(X-\mu_X)^2}{(\Sigma X_i-\mu_X)^2}\right\}}$$

The $\hat{sY}$ values are then used to place the confidence limits about the regression line. The confidence limits obtained this way are curved lines, which are closest to the regression line around the point X Y, and curve away towards the ends of the distribution.

In order to plot the 99.9% prediction limit of the regression line, $\hat{sY}$ is multiplied by a value equal to 3.291 which is the students $t_{0.01}$ value corresponding to a two-tailed test with N-1 degrees of freedom.

In the cumulative distribution curves, the correlation coefficient between the actual data cumulative frequency distribution and the cumulative normal is obtained from the equation:

$$\rho_{XY} = \frac{Cov(X,Y)}{\sigma_X \sigma_Y}$$

Where: $-1 \le \rho_{XY} \le 1$

$$Cov(X,Y) = \frac{1}{N}\sum_{i=1}^{N}(X_i-\mu_X)(Y_i-\mu_Y)$$

APPENDIX E

Derived Grade Stresses and Moduli of Elasticity for Seasoned Pine Timber Grown in Kenya.

Results type	Grade	Bending parallel to grains (MOR) N/mm^2	Tension parallel to grains N/mm^2	Compression Parallel to grains N/mm^2	Shear parallel to grains N/mm^2	Modulus of Elasticity	
						Mean N/mm^2	Minimum N/mm^2
MOPW	SS	4.3	2.6	4.3	0.9	11800	4300
	GS	3.0	1.8	3.6	0.9	10600	3900
Direct	SS	3.2	1.3	3.2	1.1	11300	4300
	GS	2.2	1.0	2.2	1.1	10200	3900
Trimmed	SS	3.9	1.6	3.7	1.3	10900	4600
	GS	2.7	1.2	2.6	1.3	9800	4100
Transformed*	SS	6.2	2.6	6.4	1.5	10500	4600
	GS	4.4	1.9	4.5	1.5	9500	4100

*The grade stresses for transformed data are recommended here for use in structural design

APPENDIX F

Green to Dry Increase Factors for Kenya Pines (Harley 1993)

Strength Property	Green to Dry Strength increase Factor
Modulus of rupture	1.89
Modulus of elasticity	1.12
Compression parallel to grains	2.08
Shear parallel to grains	2.10

Specimen Sampling Districts and Sawmills

District	sawmill
Elgeyo Markwet	Elgeyo
	Wareng
Kakamega	Sembi
Kericho	Frankways
	Sorget
Kiambu	Eastern Rift
	Sasumua
Nandi	Bhangra

District	sawmill
Laikipia	Mills Complex
	Muinami
Meru	Kamburi
	Rindikiri
Nakuru	Amalgamated
	FITC
Nyeri	Mount Kenya
	Ichuga

10 pieces of timber were obtained from each sawmill
A maximum of three specimens was obtained from each piece of timber.