A STUDY TO TEST THE COMPLIANCE OF VARIOUS PLYWOODS (KENYAN *PINUS RADIATA*, EUROPEAN *BETULA PUBESCENS* AND METSA) WITH EUROPEAN STANDARDS

A Dissertation Submitted to the University of Wales in Partial Fulfilment of the Requirements of the Award of the Degree of Master of Science in Biocomposite Technology

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DEDICATION

To my dear wife, Gladys for her encouragement and for shouldering the responsibility of caring for our family. To my sons, Sam, for managing to start primary school without fatherly encouragement and Mark, born whist I was away. Also to my mother and father, brothers and sisters for their daily prayers which sustained me throughout the period of my studies. Finally to all my relatives and friends of goodwill who availed my family moral and spiritual support.

DECLARATION

I hereby declare that this dissertation, being submitted in partial fulfilment of the requirements for the degree of Master of Science in Bio-Composite Technology in the University of Wales, Bangor, UK., has not already been submitted or accepted in whole or part of any degree, and is not being submitted for any other degree.

I also certify that this study is the result of my own investigation and wherever I am indebted to anyone, such persons are acknowledged.

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ABSTRACT

The compliance to European standards of Kenyan *pinus radiata* plywood and European birch and metsa plywood used in the UK was investigated. Methods and materials used for sampling, the preparation, testing of specimens and data analysis have been outlined as well as the standards used. Average density, bending strength and stiffness in bending and tensile shear strength values have been obtained and are discussed and compared with previous relevant work. It was concluded that only European metsa plywood and 3 mm, 3-ply Kenyan plywood met the bonding quality requirements for plywood given in BS EN 310 (1995). The bonding quality performance of Kenyan and European birch was generally poor and probable causes have been pointed out. It was recommended that further research work be undertaken to establish specific causes of low mechanical properties and poor bonding quality performance, and propose possible ways of improving plywood.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background

Plywood is usually subjected to factory and industrial standards to control both the raw material and the production processes, such as the quality of the raw material, viscosity of glue or binder and also to build confidence in the product and to assist in progressive and stable marketing of the product. National standards which are either autonomous or semi-autonomous and are sponsored by governments, ensure that consumer's and manufacturer's interests are catered (FAO, 1966).

The availability of national and international standards on constructional materials (including plywood) in many industrialised countries make it easier for building engineers, architects and other users during design. British and European standards and test methods have been in use for many years, as well as American and Japanese. Most developing countries have relied on standards from these countries, although the way forward must be to develop and rationalise test methods and procedures appropriate to their own materials.

Material testing and methods are essential components in standards and specifications and the first FAO conference in 1949 recognised the importance of agreement on test methods for plywood, for example tests for measuring mechanical properties of veneer, plywood and other glued veneer constructions, for obtaining data for design purposes and determining the effect of strength of treatments and methods for determining physical and mechanical properties (FAO,1996).

Like in many countries, Kenya has carried out a considerable amount of work on physical and mechanical properties of its major constructional sawn timber using small clear specimens prepared from cypress and pine. Visual stress grading, based on KS0771:989 specification, combined with strength values generated from small clear testing have resulted in the availability of permissible grade stresses for use by building engineers. Further testing of the same species using full size members is ongoing (Ng'ang'a, 1993; Harley, 1994).

According to FAO (1991), developing countries still use the highest amount of plywood. About 80 % and 30 % of wood-based panel boards produced in the world is plywood from developing and developed countries respectively: more than 90 % of that produced is exported to industrialised countries. Nevertheless, very little technical information is available on these constructional materials, the most important in Kenya being plywood, particleboard and block boards.

Information on their mechanical properties, quality, biodegradation, markets and costs, among others, is very necessary. A national standard for Kenyan plywood is not available except a draft standard which was prepared by the Plywood Standards Committee under the guidance of the Building Industry Standards Committee. The standard sets out five principle grades of plywood including a grade suitable for high architectural finished surfaces. However even the draft is not available to the producers and production control is hampered by lack of product knowledge (KS02-301:1983).

Due to this gap in knowledge, there is an urgent need to generate information on plywood manufactured in Kenya: species type(s) used and resource availability, possible alternative species, physical and mechanical properties, resistance to attack by biodegrading agents and quality classification. This would be useful in developing a national standard for plywood which will make it easier for producers, users and those marketing plywood. This paper proposes to test the compliance of *Pinus radiata* plywood manufactured in Kenya and European [Metsa and *Betula pubescens* (birch)] to European Standards.

1.2 Overall Objective

To test the compliance of physical and mechanical properties of plywood manufactured in Kenya and European [metsa and *Betula pubescens* (birch)] plywood to European Standards.

1.2.1 Specific Objectives

1. Determine density of Kenyan *Pinus radiata*, European *B. pubescens* and Metsa Plywood.

2. Establish bonding quality of Kenyan *Pinus radiata*, European [*B. pubescens* and Metsa] plywood.
3. Establish bending strength (parallel and perpendicular to face grain) of plywood.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

Plywood is defined as a wood-based panel product consisting of an assembly of plies bonded together, some or all of which are wood. Normally the direction of the grain in adjacent plies is at right angles, with the outer and inner plies placed symmetrically on each side of a core or central ply. The main categories are "veneer" and "core" plywood. In veneer plywood, all plies are made of veneers up to 7 mm thick orientated with planes parallel to surface. Core plywood is subdivided into wood core, cellular and composite plywood (Desch, 1996 and BS, 1984).

Much research has been done on plywood and many papers published in reputable journals and a comprehensive literature review is necessary. In this review a historical background of plywood and research work relating to raw materials, manufacturing and production processes and properties of plywood is reported.

2.2 History of plywood

The earliest evidence of the art of veneering was found around 3000 B.C. in ancient Egypt where thin sheets of veneer were found, hand hewn, spread with animal glue and superimposed upon each other and weighted down with sandbags. Since then the history of plywood has revolved around its demand, resource changes and rising costs (Desch, 1996 and Perry, 1947).

In the beginning of the 19^{th} century in Greece, the art of softwood plywood making began with the need for wood splints to ignite street lamps. This led to the production of thin wood slivers from veneer stock peeled on rotary lathes. The first rudimentary plywood plant, without a pressing unit, glue spreader, veneer clipper or sander, was constructed in America in 1904 to provide panels to door manufacturers.
Early glues of starch and animal base were used for plywood production. i.e. animal and hide glues, casein, soyabean glue and blood-albumen glue. Raw materials of less expensive varieties were used e.g. alder, ash, beech, birch, pines and Douglas fir (Dick, 1963).

The first world war and door manufacturers contributed enormously to the rapid growth of the plywood industry. Aircraft factories required large quantities of thin plywood and the development of the plywood industry kept pace with that of the aeroplane. Research was intensified to perfect waterproof glues and a thorough sound plywood was marketed. (Dick, 1963 and Baldwin, 1975).

From 1921 onwards many developments were made: a technique was developed to separate heartwood from sapwood, which improved dryer production by over 30%. Dryer temperature were increased by installing new boilers which shortened dryer schedules. Speeding up blower fans also increased air flow and shortened the schedules on dryers. Then the Fenalson automatic clipper, the first semi-automatic chain-feed clipper was introduced. Later a dryer unloader was designed. With increasing plywood demand, output and efficiency increased. As the industry grew, shortages of flawless peeler logs of large diameters led to the development of machines which used small diameter logs.

By 1935 the softwood plywood industry had spread widely to draw on a more diverse raw material base and production systems had improved markedly. The plywood products were increasingly standardised and the industry had formed a highly innovative and motivated industry had developed (Baldwin, 1975).

During the second world war further notable progress was made in England and North America: resin-bonded plywood, waterproof and with uniform strength was manufactured. The mid-twentieth century might be called "plywood era" because of the high demand for plywood for use in war, on land, sea and air

2.3 Raw Materials

2.3.1 Wood Types

Wood materials for veneer and plywood manufacture vary depending on quality and type of plywood but they are mainly high quality tropical hardwoods and softwoods of the pinaceae family, e.g. pine, fir, larch, spruce, hemlock. Dipterocarpaceae family for hardwood (birch) and the meliaceae family are important for high grade veneer (FAO, 1996).

For many years, Douglas-fir and later Southern Yellow pine were the most important species for plywood manufacture in America. All other major softwoods including true-firs, western hemlock and western pines were utilised. Almost all important hardwood species are also used to some extent for plywood manufacture. Woods for softwood plywood are grouped by stiffness and strength properties. Lower density species are often used for cores and the plywood is faced with more expensive hardwoods (Haygreen and Bowyer, 1982).

According to Haygreen and Bowyer (1982), there are many factors affecting the utilisation of timber for plywood:

1. Size - Early 1920s plywood production depended on large, high quality logs. Logs less than 165 cm in diameter or with any end defects were unacceptable. Presently many mills use materials that average 25 - 30 cm in diameter.
2. Technology - This has improved continuously with the increasing scarcity of large logs, thus smaller logs could be used for veneer production. Lathes have been developed to peel veneer down to 9 cm cores. Means have also been developed to load blocks rapidly into lathes.
3. Competition for other uses - Because of high prices for top grades of lumber and because sheathing grades of plywood can be produced from logs of intermediate quality, logs with fewest knots and other defects are directed to sawmills.
4. Quality of veneer logs - This is determined by the absence of knots or surface defects, by straightness and roundness and absence of end defects. Heartrot, which is common in old-growth logs, is usually undesirable. The quality of logs entering the mill is important because:
    - It controls quality and yield of veneer
    - It affects the number of logs that prove defective once on the lathe. Defective blocks can seriously reduce the production rate of a lathe.

For Southern pine veneer production, peeler blocks of size between 200 to 360 mm in diameter are well suited and may produce over 60 % good quality veneer. Blocks under 200 mm are unsuitable because veneer yield is less than 12 % of block volume. Age of logs and logs from damaged trees during harvesting affect veneer quality as well. Log quality affects both quality and quantity of rotary-cut green veneer. A 2.5 cm sweep or crook in a 20 cm diameter block reduces veneer recovery by 44 % while a 5-cm deflection in a 40.5 cm diameter block reduces veneer volume by 23 %. Hurricane damaged logs undergo fungal deterioration and pine beetles infest them resulting in logs which give rougher veneer than normal and cause gluing problems during processing (Sellers, Jr., 1985).

The optimum density for a 13 year rotation age of *Paulownia elongata* stand for plywood production is 200 and 250 trees/ha for 36 and 40 site indices respectively. This gives plywood timber yields of about 50 and 80 m^3/ha and internal rate of return of 30 and 35 %. For *Populus deltoides* in farmlands, a rotation of 4 years give the highest internal rate of return but profitability is increased if the large diameter trees are used for plywood manufacture. Veneer and plywood industries require more than 18-cm diameter logs yielding, totally or nearly, knot-free veneers (Chaturvedi, 1992, ZongRan *et al,* 1996 and Verkasalo, 1997).

According to Nath (1997) plantations of fast growing species are promoted to provide timber for plywood industry. *Anthocephalus chinensis* yield very good quality face veneer from the outer circumference of the logs, where knots are not present. Otherwise it gives veneer suitable for using as glue core and panel core. Drying and gluing of *A. chinensis* for manufacture of plywood poses no problem.

Provenance tests and clone selection on many species have been carried out in many countries with the aim of increasing the genetic base, suitability and availability of wood for plywood industries. e.g. Poplar (*Populus* species, mostly *P. Deltoides* and *P. tomentosa Carr*) (Chaturvedi *et al*, 1994 and Zhu and Zhang, 1997).

Iskandar *et al* (1994) and Tang and Chou (1996) studied the peeling characteristics of 10 and 15 year old *Hevea brasiliensis* and *Paraserianthes falcataria* and 25 cm diameter domestic fir (*Cunninghamia lanceolata*). Physical and mechanical properties of the veneer and plywood produced showed that proper silvicultural practices improved growth of the trees which provided better quality renewable wood-material for plywood manufacture.

According to Mathews *et al* (1993) *Eucalyptus grandis*, *Paraserianthes falcataria* and *Hevea brasiliensis* can be used as raw materials for the plywood industry. It was found that the timbers could be peeled well with suitable modifications in lathe settings. It was also possible to dry the veneer without any drying degrade. Gluing and bonding characteristics were good with urea formaldehyde and phenol formaldehyde resin adhesives.

2.3.2 Adhesives

The use of natural or synthetic adhesives for the manufacture of wood-based composites has made it possible to produce any size of structural element, with favourable strength to weight ratios or stiffness to weight ratios. The development of adhesives based on phenol meant that durability of properly manufactured boards was no longer a problem, i.e. boards that are capable of enduring board degrading factors to which the product is exposed under normally anticipated conditions (Oliver, 1981).

Choice of plywood adhesive depends on its durability, taking into account cost, supply and ease of handling with the equipment available. Most synthetic resins such as urea formaldehyde and phenol formaldehyde are widely used because they are more durable than natural glues and not very costly, unlike resorcinol-formaldehyde and melamine formaldehyde. Urea formaldehyde is cheapest having great versatility in plywood manufacture, but it does not withstand continuous cyclic water-drying and begins to degrade at 70 °C (Sellers, 1985).

Plywood bond performance depends on the type of resin and the quality of veneer used. There are four broad categories of adhesives, described by resin type: weather and boil resistant [phenol-formaldehyde], cyclic boil resistant [e.g. melamine-urea formaldehyde], moisture resistant [urea formaldehyde] and interior [extended urea formaldehyde] . Urea formaldehyde can survive full exposure to weather for a few years. It also withstands cold water for long periods and hot water for short periods, but not boiling water. It is resistant to attack by micro-organisms (BRE, 1994).

Phenol formaldehyde is produced from phenol and formaldehyde units present in coal tar. It is one of the "hot-setting" phenolic glues which are of greatest importance for plywood industry. It is usually produced with a molar ratio of about 2 - 2.5 formaldehyde to 1 of phenol. Its storage life is 2 - 3 months and its pressing temperatures range between 135 to 160 °C. Urea formaldehyde raw materials are coal, water and air from which urea and formaldehyde units are produced. The storage life of urea formaldehyde liquid glues is approximately 3 months at 18 °C; powder glues last about 1 year under normal conditions (Kollman, 1975).

According to Haygreen and Bowyer (1982), a typical adhesive mix for Southern pine plywood is:

Component	Weight (kg)
1. PF resin (40 % solids)	227
2. Water	66
3. Furafil	43
4. Wheat flour	9
5. Caustic soda	9.5

The rate of adhesive application to the veneer ranges from 16 - 20 kg of adhesive per 90 m^2 of single glueline. Thus 90 m^2 of 3-ply plywood (2 gluelines) requires 32 - 40 kg of adhesive mix.

According to Oliver (1981), the role of lignin, bark and foliage as adhesives has been partially defined by laboratory and industrial experience. Some commercial use has been made of these naturally derived resins in New Zealand, Scandinavia, India and South Africa. However their future use would depend on further understanding of their chemical and physical properties and their knowledge of sources: in particular raw material availability, aging effects, material separation and purification and influence of co-reactants (Oliver, 1981 and Haygreen and Bowyer, 1982).

Black liquor from pine needles can replace up to between 30 % and 50 % of phenol in the production of plywood which meets boil and waterproof and weather and boil resistant grade requirements respectively (Klasnja, and Kopitovic, 1992).

Lignosulfonate isolated from sodium based spent sulfite liquor from paper mills can replace upto 70 % of phenol for the manufacture of exterior grade plywood (Mansoor and Tasleem, 1992).

Kraft lignin from poplar (*Populus*) and willow (*Salix*) wood can also substitute up to 50 % phenol in the resin composition and give satisfactory shear strength in plywood (Singh and Singh, 1994).

Wattle (*Acacia mearnsii*) tannin adhesives are prepared by substituting paraformaldehyde with phenol formaldehyde and phenol-urea-formaldehyde resins as cross-linking agents. It has been used to produce exterior plywood whose bonding and tensile strengths meet the standard for first and exterior grade plywood respectively (Zhao *et al,* 1993 and 1995).

According Song *et al* (1990) tannin bark extracts from *Pinus densiflora* and *P. rigida* can replace about 50 % of phenol-formaldehyde resin for exterior grade plywood, and about 70 % for interior grade.

By hydroxyphenylation and hydromethylation, Wei *et al* (1992) made adhesives for plywood from phenol formaldehyde and straw alkali lignin (separated from pulp black liquor). They also made the adhesives from dilute sulphuric acid lignin using concentrated sulphuric acid hydrolysis lignin for comparison.

With regard to health and safety, recommended sources of phenolic compounds in plywood are wood components (lignin and extractives), phenol-formaldehyde resin adhesive, and ligno-cellulosic adhesive fillers (bark tannins, furfural residue lignins, etc.).

Analysis of construction-grade plywood panels for total phenolic compounds and free phenol show that the levels of phenolic compounds and free phenol in plywood are so low that structural wood composites bonded with phenol-formaldehyde resins are very safe environmentally for multiple uses (Tiedeman *et al*, 1994).

Urea formaldehyde resin is the most utilised binder, accounting for 90 % of the market share. Although it releases formaldehyde and water during hardening on the press, its emission is reduced by using suitable hoods and linings to ventilate and draw the gaseous pollutants away. The amount of formaldehyde released by PF is very small compared to UF but it is the cheapest (Khoo, 1993).

According to Meyer (1986) formaldehyde release from wood products has been decreasing by a factor of more than 10 for over two decades. Many industries are capable of meeting the 0.4 ppm standard. In Europe, the low emitting products (which account for 20 % of total production) meet 0.1 ppm air levels. This is achieved by using low formaldehyde to urea molar ratio resins, addition of urea to resin or wood furnish before resination and post-treatment of hot board with ammonia or ammonia salts as well as improved quality control systems.

Formaldehyde emission and glue-joint strength of plywood are reduced by decreasing the final molar ratio of formaldehyde to urea in UF resins. But adding p-toluene sulfonic acid as a hardener and corn gluten as a filler to the conventional resin formulation system improves bonding strength (Roh and Kim, 1997; Sutigno and Santoso, 1995 and Boehme, 1994).

For softwood plywood, development of phenolic glues for use with veneers at 10 % moisture content or more instead of 3 - 4 % was a breakthrough. It resulted in higher dryer productivity, improved press productivity, lowered glue spreads, better pre-pressing and assembly time tolerances, improved veneer gluability and fewer panel blows. Some plants saved up to 22 % in glue cost while simultaneously saving on dryer and press costs. Gluing high moisture content veneer up to 15 % results in product close to equilibrium value in actual use, thus decreasing warp and dimensional changes (Maloney, 1993).

According to Roh *et al* (1995) and Tohmura (1998), sodium carbonate as a cure-accelerating agent in plywood bonding has the greatest effect on shortening gelation time of phenolic resin. An addition of 5 parts sodium carbonate can shorten hot-pressing time of phenol resin by about 20 %. Addition of merbau (*Intsia sp.*) wood extractives also slightly increased the gelation rate of phenolic resin. A combination of cure acceleration and surface brushing greatly improved bonding properties.

Yamaguchi *et al* (1994) found that the water-resistance of plywood made using a hot-press method in which gelatin-powder is scattered on veneer surface spread with tannin solution, markedly improved because the melting of the gelatin by heat and water and mixing of the two reactants occurred. Waterproof properties of adhesives produced as a result of a tannin-gelatin complex are best when persimmon juice is used as the source of tannin.

An investigation into viscosity changes in melamine-urea-formaldehyde glue line using a thermomechanical analyser (TMA) showed that increasing temperature decreases glue line viscosity until a minimum is reached, after which a rapid viscosity increase occurs due to the advancement of cure reaction. TMA is suitable for modelling hot pressing process and measuring *in situ* the glue line viscosity change during the early stage of cure (Yin *et al,* 1997).

Faust and Borders (1992) used variable glue spread rates to control bond quality and reduce glue consumption in pine plywood production. The results showed that a variable application rate strategy (VARS) yielded an 8.3 % higher average wood failure than a constant application rate, while using 13.1 % less adhesive. VARS was particularly effective in eliminating the detrimental effects of veneer roughness on bond quality.

Shear strength and wood failure are not significantly affected by gluing errors. But the use of very wet or very dry veneers and the incorporation of a long pre-settling time significantly reduce strength (Suomi *et al,* 1986).

De-oiled maize gluten is better as an extender with liquid urea formaldehyde resin than tamarind seed powder and de-oiled groundnut cake although groundnut cake powder performs better with powdered urea formaldehyde resin. Protein or starch extenders also perform very well with phenolic formaldehyde resin in boiling water-resistant and boiling water-proof plywood (Mohandas *et al,* 1993 and Raghunath and Zoolagud, 1993).

2.4 Production/Manufacturing and Uses

2.4.1 Production Process

For a firm to remain competitive, it must allocate financial resources into areas that will maintain or improve its performance. Research on firms responsible for over 70 % of softwood plywood production show that increased adoption of innovative processing technologies is linked to superior performance. Companies with high levels of adoption exhibit average to better-than-average levels of profitability and command a higher market share for their products (Cohen and Sinclair, 1990).

In plywood manufacture there are five basic steps involved after the logs have been cut to lengths required for rotary veneer cutting and then debarked. They are heating of blocks, cutting veneer, veneer storage and clipping, veneer drying and lay-up and pressing (FAO, 1996 and Haygreen and Bowyer, 1982).

The purpose of heating of the blocks is to soften the wood and knots to make it easier to cut, and to improve surface quality and reduce roughness. In softwood logs, this leads to four main advantages:

- Higher yields of veneer from logs
- Improved veneer grade
- Reduced labour costs through reduced handling because veneer is able to hang together in a continuous ribbon as it comes off the lathe
- Reduced amounts of adhesive used; glue spreads are lighter because of the improved surface

The methods used for heating logs are steaming, soaking in hot water, spraying with water or a combination of the two. Dense hardwoods are heated by soaking at temperatures up to 93 °C. For most Southern pines, a temperature range of 49 °C - 71 °C is recommended for rotary peeling. Most mills have developed heating schedules based on trial and error or by measuring log temperatures as the block peels. Heating time depends on diameter of log, specific gravity, moisture content and temperatures needed to properly peel, species but it is generally 8 or more hours. The higher the density, the higher the optimum temperature for cutting veneer, for example basswood cuts well at 16 °C while white oak requires 93 °C (Sellers, Jr., 1985 and Haygreen and Bowyer, 1982).

Veneer cutting in plywood manufacture is done by either slicing or peeling (rotary cutting). Slicing is used for producing high quality hardwood veneer. Peeling is commonly carried out on a veneer lathe. High-speed production in modern mills uses automated equipment to load (charge) the lathe with small blocks, round up the bolt, and peel the veneer down to a 10 - 14 cm. They can produce the veneer and discharge the core in about 10 seconds. Mills cutting large logs commonly use less highly automated systems (Haygreen and Bowyer, 1982).

Yield of veneer (volume of veneer per unit volume of blocks) varies with log diameter, log quality (including straightness of block), diameter to which logs are peeled (core diameter) and efficiency at veneer clipping and utilisation. The greatest loss occur at the clipper; as little as 2.54 cm. of sweep or crook in a 20 cm diameter block reduce veneer yield by as much as 44 %. The ratio of core volume to total block volume increases as diameter of block decreases (Haygreen and Bowyer, 1982).

In veneer storage and clipping, a series of trays are used to handle long ribbons of veneer peeled at between 150 - 400 linear cm/sec. In hardwood mills green veneer is wound into a roll and then moved to clippers. Clippers are high speed knives that chop veneer ribbons to usable widths at speeds of up to 750 linear cm/sec. The veneer is clipped to about 140 cm. (panel width plus shrinkage and panel trimming allowance). Manual clipping is also used when there is need to maximise the amount of clear material from flitch (Haygreen and Bowyer, 1982).

According to Haygreen and Bowyer (1982) since the development of the jet (or "impingement") veneer drying method, drying times have been reduced and veneer uniformity improved. Its principle of operation involves forcing hot air at speeds of up to 2000 cm/sec through small tubes, impinging on the veneer. In softwood veneers temperatures over 204 °C have been found to have adverse effects on gluability and emission of undesirable gases.

Work by Narayanaprasad and Rangaraju (1997) showed that the optimum temperature for drying *Dipterocarpus* species (keruing) and *Grevillea robusta* (silver oak) veneers in thermic fluid heated dryers is 180 °C and 220 °C for urea formaldehyde resin and for both phenol formaldehyde and urea formaldehyde resin adhesives respectively.

In plywood manufacture, veneer lay-up and pressing is the most labour intensive stage and involves the process of applying adhesives to veneers, assembling veneers into panels and moving panels in and out of a press. Spray and curtain coaters are preferred to automated systems because they have advantages of uniformity of glue spread and overcome the problem of poor glue spread on rough stock (Nath, 1996).

Manufacture of veneers having thickness variations of over 0.51 mm for Southern pine is considered impractical because the phenolic adhesives used are not gap-filling. Plywood adhesive bond quality decreases as quantity and degree of uneven veneer increases. Moreover smoother veneer decreases glue consumption for an adequate glue-bond, reduces knife wear on the lathe for peeling and increases the chance of good, wood failures (Sellers, Jr., 1985).

In most softwood plants, prepressing (or "cold pressing") of plywood assemblies is usually incorporated into commercial production without incurring high costs or introducing automatic equipment or major changes in the process or plant layout. It is done in a cold press at lower pressure and it permits easier loading of the hot-press and helps prevent shifting of veneers during loading (Haygreen and Bowyer, 1982).

Veneer pressing is done in multi-opening presses which can produce 20 to 40, 120 x 240 cm panels in each pressing cycle, each taking between 2 - 7 minutes. The purpose of pressing is to bring the veneers into close contact so that the glue line is very thin, and to heat resin to temperatures required for the glue to polymerize. Adhesives made from phenol formaldehyde resins typically require 115.5 °C in the innermost gluelines for about 90 seconds to cure properly. Pressing pressures vary from 110 psi for low density woods to over 200 psi for dense species (Haygreen and Bowyer, 1982).

Dimri *et al* (1990) studied pressing conditions of plywood from *Populus ciliata*. The required shear strength for WWR (warm water resistant) plywood was achieved in 9 minutes at 14.0 kg/cm^2 pressure: increasing the pressure reduced the time required. Compression loss increased more with an increase in pressure than with increase in pressing duration, and was accompanied by an increase in panel strength; loss tended to become too high (about 20 %) at 17.5 kg/cm^2 pressure.

According to Sellers, Jr. (1985) adhesive spreads, moisture content, pressing time, stand time before pressing, veneer temperatures, pressure, veneer quality, adhesive mix viscosity and the adhesive application method affect the wood bond. Studies on vacuum-pressure shear test show that curtain coater application methods yield 13 % higher wood failure on rough veneer than roller spreaders.

2.4.2 Uses of plywood

The highest volume of structural plywood is used in building construction for sheathing, subflooring, formwork (shuttering), interior wall panelling and inside fittings. It finds much application in exhibition halls, theatres, churches, concert halls, railways, ships and to some extent, the motor-car industry. It is preferred due to its many advantages, for example its superior strength, non-splitting qualities, good dimensional stability, availability in relatively large sizes, favourable strength to weight factors, development of matched and symmetrical faces, reinforcing fragile veneer and easiness to curve (FAO, 1966; Rinne, 1952 and Perry, 1947).

For the proper use of plywood, four main requirements have to be met, namely:

- Durability required of the glueline to avoid delamination
- Strength, stiffness and nail-holding requirements
- Visual quality or appearance

- Special requirements, e.g. decay or fire resistance

According to FAO (1996), density and appearance affect the use characteristics and utility of plywood. Wood density ranges from about 400 Kg/m^3 to 700 Kg/m^3 (air-dry) but species with densities of between 500 - 550 Kg/m^3 are preferred for plywood manufacture. Lustre varies from wood to wood and is more prevalent in hardwood than softwood; even colour is desired, although sometimes a plain colour is desired for embossing striated patterns or imprinting grain patterns. Compression wood with abnormal longitudinal shrinkage can cause imbalance, warping and even cracking across the grain of adjacent plies. Tension wood gives a fuzzy appearance after sanding plywood. Knots are only allowed according to grade specifications.

Classification and performance requirements for most wood-based sheet materials are available based on strength and stiffness properties and strength or capacity groupings. Plywood is used in many climatic conditions due to innovative research to improve its performance (Carruthers and Abbott, Robinson *et al* and Kearley *et al,* 1991).

2.5 Physical and mechanical properties

The physical and mechanical properties of plywood are influenced by the species type, the adhesive and the method of manufacture. The cross-banding construction of plywood from timber veneers also plays a significant role in influencing the properties: it imparts high longitudinal strength in two directions. Tensile, shear and bending strength, stiffness and dimensional stability of plywood are approximately equal along and across the plane of boards. Strength increases with increasing number of plies upto 7-ply and in practice a 3-ply board, 150 cm wide , even when exposed to damp, will not swell and more than 1 mm (Desch, 1996 and Wood, 1963).

Plywood is classified into three classes on the basis of bonding quality; class 1 is a bonding class appropriate for normal interior climate, class 2 for protected external applications (but capable of resisting weather exposure for short periods) and class 3 for exterior conditions. Plywood for use in dry conditions is defined as plywood used only in interior applications with no risk of wetting (BS EN 636-1, 1997).

2.5.1 Physical Properties

According to BS EN 314-2 (1993) density is determined as the ratio of mass to volume of plywood both measured at the same moisture content. It is generally higher than density of the wood from where veneer is manufactured, although it depends largely on the quantity of adhesive used.

Like sawnwood, plywood is hygroscopic and its moisture content depends on the surrounding temperature and relative humidity. Equilibrium moisture content of plywood for interior use is less than that of solid wood due to presence of glue lines. Under normal conditions face veneers pick up and shed moisture relatively fast but subsequent layers are protected by glue lines which impede entry of moisture (TRADA, 1972).

The equilibrium moisture content of plywood is usually characterised by moisture content in material corresponding to 20 ° C temperature and 65 % relative humidity. The EMC influences the plywood tolerances on dimensions, bonding quality, biological durability and mechanical properties (EN 314-2, 1993).

When plywood is exposed to a constant relative humidity, it eventually reaches an EMC. The EMC is highly dependent on relative humidity, but is essentially independent of temperature between 0°C and 85°C (Schniewind, 1989).

The dimensional stability of plywood is affected by the arrangement and quality of the plies, the moisture content and the expansion or contraction of plies. Balanced cross-banding construction eliminates shrinking and swelling in the plane of the boards caused by moisture content changes. However, changes in moisture content induces large stresses in outer glue joints because outer or face plies of cross-banded construction are restrained on only one side. The magnitude of these stresses depends on the thickness of the outer plies, the density of the veneer and the rate and amount of moisture content. Such stresses can cause face checking, but generally the thinner the face veneer the less the face checking (Anon, 1989).

Plywood made of straight grained, smoothly cut and sound wood plies has high dimensional stability. Cross-grain that runs sharply through cross-band veneer from one face to the other causes panel cupping, while cross-grain that runs diagonally causes twist. Changes in atmospheric moisture conditions or wetting of the surface by free water tends to warp plywood panels and can affect the surface appearance. In hot-pressed panels water is lost from the adhesive and the wood during heating. To minimise dimensional changes and problems associated with them, panels are conditioned at a relative humidity as close as possible to service conditions (Anon, 1989).

The dimensional stability of plywood is associated with moisture and thermal changes: it involves not only cupping, twisting and bowing but also expansion and contraction. Shrinking and swelling of plywood is effectively reduced because grain directions of adjacent layers are placed at right angles. The low dimensional changes parallel to the grain in one layer restrains normal swelling and shrinking across the grain in the layer glued to it. Additional restraint results from the fact that modulus of elasticity parallel to the grain is 20 times that across the grain. Plywood expansion or contraction is about equal to the parallel to the grain movement of the wood species of the veneers. Dimensional change of plywood in thickness does not differ from that of solid wood (Anon, 1989).

According to Santoso and Sutigno (1995) veneer thickness has no significant effect on plywood bonding strength but glue spread has a significant effect. 150 g/m^2 per face of glue spread with urea formaldehyde adhesive is recommended for plywood for interior use.

According to Huang and Shi (1996) making 3-ply plywood from mixed or unmixed poplar veneer using urea-formaldehyde resin low in free formaldehyde content does not affect its bonding strength. However the dosage of curing agent has considerable influence on bonding strength.

Plywood made from *Pinus roxburghii* veneers of 3 thicknesses and bonded with phenol-formaldehyde resin with arsenic trioxide at 5 different concentrations was exposed to termites (*Microtermes beesoni*). Analysis showed that there were some statistically significant differences between the arsenic-treated and untreated specimens in wet glue shear strength and bending strength. Plywood made with thicker veneers was more susceptible to termite attack than that made with thinner veneers (Shukla and Joshi, 1992).

A comparison of bonding properties between a wood-plastic composite veneer and plywood using different adhesives showed that phenol resin, water based polymer-isocyanate adhesives and oilic urethane are equal in strength but greater than phenol-resorcinol and phenol-melamine which is also greater than urea-melamine resin. In the case of bonding with phenol-melamine, and oilic urethane resin, the delamination ratio was higher with an increased impregnation ratio of resin into veneer. Hardness increased with increasing impregnation ratio of resin to veneer. Maple and oak veneer impregnated to 100 % and 60 % improved by about 50 % and 20 % respectively over non-impregnated veneer (Roh and Kim, 1997).

Treatment of face veneer of modified beech (*Fagus sylvatica*) plywood with phenol resin increases adhesion with increased penetration of phenol formaldehyde resin: at 46 % and 56 % penetration, adhesion is comparable to that of bakelized plywood (PF-resin impregnated plywood) (Jablonski *et al,* 1997).

Acoustic emissions from a core ply have greater amplitudes than those from the region near the glue-line, particularly for specimens of great bond strengths. This indicates that sound released from the vicinity of glueline is less than away from it (Ohtsuka *et al,* 1993).

Compared to emulsion paint and polyurethane, synthetic enamel is the most effective coating at maintaining glue bond, modulus of rupture (MOR) and modulus of elasticity (MOE) for Vellapine (*Vateria indica*) 5-ply plywood exposed to weathering conditions. Wood failure of plywood from *Pinus radiata* treated to 5 kg Copper Chrome Arsenate (CCA) per m^3 decrease significantly over time both for exterior and interior panels. Uncoated melamine-urea formaldehyde panels fail completely after 12 years. Uncoated panels with CCA treatment has less wood failure than either the untreated or the copper naphthenate treated panels (McLaughlan, 1991 and Damodaran *et al,* 1995).

Wood element size and orientation are dominant factors in determining thermal response of wood and wood composites. In dried wood of *Pseudotsuga menziesii* and *Populus tremuloides*, longitudinal thermal movement decrease in dimension during heating while radial and tangential movement increase under similar heating conditions. Oriented foams show more restraint in thermal movement in the parallel to orientation direction. On the other hand, thermal conductivity of plywood has the same value as that of wood of same species and density (Chow, 1994 and Anon, 1989).

2.5.2 Mechanical Properties

2.5.2.1 Modulus of rupture and modulus of elasticity

The mechanical properties of plywood are affected by many factors: the number and thickness of veneers, wood species, moisture content and adhesive type and content. The type of stresses, direction of stress in relation to grain direction of face veneer to span and the duration of load also influence these properties (Bier, 1984).

Work by BRE (1995), showed that plywood constructed from thin veneer give two to three times the bending and tension strength of standard plywood. Increasing plywood thickness was also found to increase the strength. It was also found that the highest plywood strength values are obtained by using smaller glue spread levels than those used in commercial production. An increase in adhesive content is not very beneficial to most mechanical properties.

According to Kollman *et al* (1975), the modulus of rupture of plywood for face parallel to span shows a positive linear regression to density (wide range of scattering) in 4.5 mm, 3-ply of different species. An increase in the number of gluelines in plywood comprising veneers of less than about 23 mm thick produces an increase in strength. It has been shown that perpendicular to the span veneers contribute very little to the stiffness and strength of plywood.

In terms of ply construction, bending properties parallel to face grain of *Pinus radiata* plywood are better for 5-ply than 7-ply; their bending strength (particularly when the face grain is parallel to the span) can be predicted using a matrix format to determine the position of the neutral axis and the moment capacity of the cross section (Booth, 1990).

The bending strength and stiffness of wood based panel members for structural use varies depending on the type of raw materials used. The deflections in bending and creep show that Tropical Hardwood Plywood (THP) < Siberian Spruce (SP) < Oriented Strand Board (OSB) < Medium Density Fibreboard (MDF) < Particleboard (PB). For dry-test bending properties, THP > MP > MDF > SP > OSB and PB. Retention of strength properties under accelerated aging is less for composite than for plywood panels (Park and Seo, 1995).

Plywood has high strength in bending than solid timber due to the distribution of high longitudinal strength in the cross-banding construction (Bier, 1984).

Research work by Suh (1996) showed that the dry and wet bending strength of plywood for interior construction or concrete formwork is increased by painting and overlays.

Suh and Kim (1995) investigated flexural behaviour of plywood using softwood for concrete formwork. Their results indicated that:

- plywood using *P. radiata* as a facing layer showed a relatively high dry or wet MOR compared with *Terminalia* species faced with softwood
- bending strength of 5-ply is greater than for 7-ply, except for the softwood 7-ply bonded with phenol resin
- bending strength and displacement at bending failure tend to increase with use of phenol resin
- a 5-ply hardwood and softwood combination plywood with phenol resin glue satisfies the standard for flexural rigidity

2.5.2.2 Shear strength

The shear strength of plywood in different directions is difficult to determine with certainty. Even if shear tests are properly carried out, the values obtained are not generally applicable in practice. This is because of the edge effects of various kinds and the size of the plywood (Kollmann, 1975).

Compared with solid timber, plywood has a high strength in shear due to the distribution of high longitudinal strength in the cross-banding construction (Bier, 1984).

According to BRE (1995), the ratio of longitudinal modulus of elasticity to rolling shear stiffness is as high as 500 : 1 in dry conditions and even higher in wet conditions: this means that studies on transverse shear behaviour are very important.

Work by Palka (1978) found that the rolling shear properties (failure stress and modulus of rigidity) of single species, unsanded, sheathing grade plywood manufactured from thick natural (unpatched) veneers using phenol formaldehyde glue is fairly uniform within mills.

Work by Kamiya *et al* (1997) found that plywood contributes to high shear strength in plywood -sheathed walls and floors.

According to BRE (1995) modulus of elasticity and interlaminar shear modulus of birch plywood decreased with increasing moisture content. For example, the shear strength of 1.4 mm and 3.2 mm thick spruce veneers (2.83 MPa and 1.97 MPa respectively) decreased with increasing veneer thickness. This was attributed to the size and number of rotary peeling cracks and the thickness of cross-wise layers.

2.5.2.3 Creep

Plywood construction and external factors are some of the factors that affect creep behaviour in plywood. Board construction is influenced by particle size, resin type and amount and anisotropy. Thus creep increases and duration of load decreases in the order - timber, plywood, OSB, particleboard and fibreboard- since the smaller the particle size, the greater the propensity of plywood to creep. There is increasing propensity for plywood to creep with melamine-urea formaldehyde, urea formaldehyde, phenol formaldehyde, isocyanate and high alkaline cured formaldehyde (BRE, 1995).

External factors that influence creep include the mode of stressing, the time under load (whether constant or alternating), the level of stressing, the temperature and the relative humidity. Creep under shear is usually greater than in pure bending. On the other hand, creep, although very fast initially, slows down progressively over the remainder of the life of the sample before increasing immediately prior to failure. An increase in the level of stressing results in a marked increase in creep and a reduction in the time to failure. Increasing temperature causes a small but significant increase in the rate of creep. Increasing steady-state relative humidity and moisture content results in increasing creep deflection and decreasing time to failure (BRE, 1995).

The creep behaviour of plywood under permanent load and alternate climate is also primarily influenced by the composition of plywood. Plywoods bonded with low content formaldehyde show no noticeable higher long-term bending behaviour (BRE, 1995).

According to Suh and Kim (1995), there are no significant differences between softwood and hardwood plywood as regards creep, although a 5-ply performs better than a 7-ply construction

2.5.2.4 Effect of wood treatments

Research on the influence of wood preservative treatments on the mechanical strength of plywood has shown that all mechanical properties of plywood decrease at higher levels of uptake of wood preservatives. Liquid retention levels of over 450 kg/m^3 (15 kg CCA salt/m^3) alter physical and mechanical properties. Other preservatives such as Copper Chrome Borate (CCB) and Copper Chrome Flourine (CCF) also reduce strength as much as CCA (BRE, 1995).

Work by Winandy *et al,* (1991) showed that treatment of Southern pine (*Pinus 'Southern'*) plywood with monoammonium-phosphate, lowered its bending and tensile strength. The strength degradation rate increased with exposure temperature.

Fire-retardant-treated plywood for roof sheathing and roof truss lumber experiences strength losses from thermal degradation in some conditions. The combination of elevated temperatures, fire retardant chemicals and moisture prematurely activate the fire retardant. The lower the pH of fire retardant-treated wood material and/or the dissociation energy of the treatment, the higher the rate of strength loss over time (Winandy, 1995).

When Southern pine plywood treated with fire-retardant chemicals was exposed to cyclic temperature variation from room temperature to 65 °C at 6 % and 12 % moisture content (MC), MOE and MOR remained relatively unchanged. But work to maximum load was most affected. Compared with plywood subjected to constant conditions of 65 °C and 12 % MC, cyclic exposure was less severe than constant temperature exposure (LeVan *et al,* 1996).

Barnes *et al,* 1996 has shown that unlike southern pine plywood, western hemlock (*Tsuga heterophylla*) plywood treated with waterborne preservatives and redried is more sensitive to redrying temperatures than to preservative treatment and losses in mechanical properties are higher. It is affected more by acidic solutions than by alkaline solutions. Treated western hemlock plywood should not be redried at temperatures in excess of 60 °C without applying some design stress reduction factors.

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Field Sampling and Sample Size

Samples of Kenyan plywood were randomly selected from Raiply plywood mills, Kenya. The plywood sheets were assembled from *Pinus radiata* veneer manufactured on a rotary lathe machine using urea formaldehyde adhesive resin. They were constructed from plies of non-uniform thickness. The samples collected were in number 12, 8, 6 and 6 boards of 3 mm (3-ply), 9 mm (5-ply), 12 mm (7-ply) and 17 mm (9-ply) thickness respectively. They were packaged in wooden ballets and covered with carton linings. The boards measured approximately 600 x 600 mm and were transported by air to the University of Wales, Bangor.

Material for comparative purposes was purchased from Jewson Ltd, Builder's merchants, in Bangor (North Wales, UK). The samples were selected randomly from 1 standard sheet of 8.5 mm (3-ply) European Birch and 9.5 mm (7-ply) Metsa plywood imported from Finland.

3.2 Specimen Preparation

Test specimens were cut from the sample boards for determining density, modulus of elasticity in bending, bending strength and bonding quality. For bending and density assessment, the specimens were selected from the boards according to BS EN 310 and 323 (1993).

Bending test specimens were cut using a circular rip saw. Cutting of specimens to testing dimensions was done according to the procedure given in BS EN 310 (1993): the specimens measured 50 ± 1 mm wide and were in lengths 20 times the nominal thickness plus 50 mm (as specified in BS EN 310 (1993)). However the 3 mm plywood was cut into 50 mm widths and were 120 mm lengths because the maximum length allowable according to the standard for 3 mm plywood is 60 mm. Each specimen was examined for defects and only defect-free specimens selected for testing.

Specimens used for determining the density were cut from near the points of failure of the bending test specimens after they had been screened and confirmed to be free of damage. The specimens for density measurement were 50 x 50 mm as specified in BS EN 323 (1993). Specimen masses were recorded three times every 24 hours until constant mass was obtained.

All specimens were conditioned according BS EN 310 (1993) to constant mass at 65 ± 5 % relative humidity and a temperature of 20 ± 2 °C. Dimensions of specimens were taken using a sliding vernier calliper. A weighing balance was used to determine the mass of the specimens.

Specimens used for determining bonding quality were prepared in accordance to BS EN 314-1 (1993). Shear test specimens were immersed for 24 hours in water at (20 ± 3) °C before being tested. The choice of the pre-treatment was based on BS EN 314-2 (1993).

3.3 Specimen Testing

Testing for the determination of modulus of elasticity in bending and of bending strength was performed both on parallel and perpendicular to the face grain using an Instron Universal Testing machine, (model 1195 with 105 KN capacity) and according to BS EN 310 (1993). The rate of loading was adjusted so that the maximum load for each thickness was reached within 60 ± 30 seconds: this was determined by running trial tests for each plywood thickness.

The bonding quality shear tests were also carried out using the same instron machine, fitted with serrated wedge type grips according to BS EN 310 (1993). The cross head moved at a constant rate of motion so that rupture occurred within 30 ± 10 seconds which was again determined by running trial tests for each plywood thickness. After test each specimen was assessed for percentage of apparent cohesive wood failure according to BS EN 314-1 (1993). Each specimen was examined after testing to check if failure was due to ultimate load or due to defects invisible during sample preparation. Those that failed due to such defects were excluded in the calculation of overall average values.

3.4 Data Analysis

The density, shear strength for bonding quality, modulus of elasticity in bending and bending strength was calculated for each test piece using the formulae given in BS EN 323, 314-1 and 310 (1993) respectively.

Density (ρ) was calculated from the formula:

$$\rho = (m / (b_1 * b_2 * t)) * 10^6, \text{ where}$$

m is mass of test specimens (g)

b_1, b_2 and t are width, breadth and thickness respectively (mm).

The modulus of elasticity E_m (in N/mm^2), of each test piece was calculated (automatically by computer) using the formula:

$$E_m = l_1^3 (F_2 - F_1) / (4bt^3 (a_2 - a_1)), \text{ where}$$

l_1 is the distance between the centres of the supports, (mm)

b and t are width and thickness respectively of the test piece, (mm)

$F_2 - F_1$ is increment in the load on the straight line portion of the load-deflection curve (N)

$a_2 - a_1$ is the increment of deflection at the mid-length of the test piece corresponding to $F_2 - F_1$

The bending strength f_m (N/mm^2) was calculated (automatically) using the formula:

$$f_m = 3 F_{max} l_1 / (2bt^2), \text{ where}$$

F_{max} is the maximum load (N)

l_1, b and t are as defined in E_m above (mm)

Shear strength was calculated (automatically) using the formula:

$f_v = F / (l * b)$, where

F is the failing force of the test piece (N)

l is the length of the shear area (mm)

b is the width of the shear area (mm)

The data was used to give average values, standard deviation, minimum and maximum density and bending strength values. The Excel computer programme was used. Analysis of Variance (two-factor, with replication) was used to test differences in strength between board thickness and between direction of face grain. Regression analysis and scatter graphs were used to determine correlation coefficients.

CHAPTER 4

4.0 RESULTS

4.1.1 Density of Kenyan plywood

Table 1 gives average density, standard deviation, minimum and maximum values for the specimens of four thicknesses of Kenyan pine plywood. The number of replicates for each thickness are given in Appendix I.

The minimum average density was 580 Kg/m^3 found in the 3 mm (3-ply) plywood while the maximum was 647 Kg/m^3 found in the 12 mm (7-ply) plywood.

Table 1(a). Average density values of four thickness sizes of Kenyan pine plywood

Plywood thickness	Average density (Kg/m^3)	Standard deviation	Minimum value (Kg/m^3)	Maximum value (Kg/m^3)
3 mm, 3-ply	579.96	59.49	489.41	683.32
9 mm, 5-ply	643.98	40.06	573.60	735.87
12 mm, 7-ply	647.09	56.61	549.61	746.19
17 mm, 9-ply	617.82	53.29	537.07	724.81

Table 1 (b) gives analyses of variance (single-factor) at a 95 % confidence level for the various thicknesses (Clarke and Cooke, 1992). It shows that there are statistical differences between the densities of all the various board thicknesses except between the 9 mm and 12 mm thicknesses.

Table 1(b). Analyses of variance between the densities of the various board thicknesses

	3 mm	9 mm	12 mm	17 mm
3 mm	-	SS	SS	SS
9 mm	SS	-	NSS	SS
12 mm	SS	NSS	-	SS
17 mm	SS	SS	SS	-

4.1.2 Density of European plywood (birch and Metsa)

Table 2 gives average density, standard deviation, minimum and maximum values of the samples of European birch and Metsa plywood as used in the UK. The number of replicates for each plywood type are given in Appendix I.

Table 2. Average density values of European Metsa and Birch plywood

Plywood thickness (mm)	Average density (Kg/m^3)	Standard deviation	minimum value (Kg/m^3)	Maximum value (Kg/m^3)
9.5 mm, 7-ply	773.24	17.84	734.00	821.33
8.5 mm, 3-ply	487.25	30.71	440.45	563.87

The European Metsa plywood had an average density of about 770 Kg/m^3 while that of the European birch plywood was about 490 Kg/m^3.

Analysis of variance (single-factor) at a 95 % confidence level showed that there was statistical differences (P = 4.58E-68) between the densities of the two plywoods.

4.1.3 A comparison of Kenyan and European plywood

Table 3 gives results of statistical analysis (single-factor) at a 95 % confidence level for the Kenyan and European plywood.

Table 3. Analyses of variance between the densities of the Kenyan and European plywoods

	Metsa	Birch
3 mm	SS	SS
9 mm	SS	SS
12 mm	SS	SS
17 mm	SS	SS

The results show that there are statistical differences between the densities of all the Kenyan board thicknesses and the European (Metsa and Birch) plywoods.

4.2 Mechanical properties

4.2.1 Kenyan plywood

Table 3 gives average values for modulus of rupture (MOR) and modulus of elasticity (MOE) (parallel and perpendicular to the grain of face veneers) of the four Kenyan plywood thicknesses. It also shows results of analyses of variance (single factor) at a 95 % confidence level between parallel and perpendicular direction of the grain of the face veneers.

Table 3. Average MOR and MOE of four Kenyan plywood sizes

		Modulus of rupture (MPa)					Modulus of elasticity (MPa)				
Plywood Thickness		Avg MOR	Stdev	Min	Max	ANOVA	Avg MOE	Stdev	Min	Max	ANOVA
3	//	50.53	31.12	19.2	114.6	SS	5019.18	5654	915.4	18187	SS
(mm)	⊥	114.33	39.78	51.8	206.8		15127.79	7722	2732	26958	
9	//	59.60	14.74	24.7	103.2	SS	6333.49	1527	3384	3234	SS
(mm)	⊥	47.36	8.77	20.4	64.75		5061.58	686	10054	6402	
12	//	56.19	13.97	29.6	87.32	NSS	5795.21	1118	3576	8466	NSS
(mm)	⊥	54.31	18.9	32.5	96.18		6203.59	2183	3356	10403	
17	//	52.05	10.60	36.8	67.72	SS	6959.30	1267	5391	9083	SS
(mm)	⊥	44.47	5.84	35.4	53.89		5179.29	480	4485	6073	

* NSS and SS stands for Not Statistically Significant and Statistically Significant

Table 4(a) gives the overall modulus of rupture and modulus of elasticity of the four thicknesses of Kenyan plywood (average of // and ⊥). It shows that the 3 mm (3-ply) plywood had the highest modulus of rupture (82 MPa) and modulus of elasticity (10073 MPa) and the 17 mm (9-ply) plywood had the least modulus of rupture (48 MPa) but not the lowest modulus of elasticity (6069 MPa).

Table 4(a). The MOR and MOE of the Kenyan plywood (average of // and ⊥ values)

Plywood thickness (mm)	Modulus of rupture (MPa)	Modulus of elasticity (MPa)
3 mm, 3-ply	82	10073
9 mm, 5-ply	53	5698
12 mm, 7-ply	55	5999
17 mm, 9-ply	48	6069

Table 4(b) also give the analyses of variance between the modulus of rupture (// and ⊥) of the various board thicknesses. For MOR parallel to the grain, all the plywood thicknesses showed that there were statistically significant differences except for the 9 mm when compared with 12 mm and 17 mm plywoods.

Table 4(b). Analyses of variance between MOR (// and ⊥ to the grain) of Kenyan plywood

//	3 mm	9 mm	12 mm	17 mm
3 mm	-	SS	SS	SS
9 mm	SS	-	NSS	NSS
12 mm	SS	NSS	-	SS
17 mm	SS	NSS	SS	-

pp	3 mm	9 mm	12 mm	17 mm
3 mm	-	SS	SS	SS
9 mm	SS	-	NSS	NSS
12 mm	SS	NSS	-	SS
17 mm	SS	NSS	SS	-

4.2.2 European plywood

Table 5(a) give the average MOR and MOE (// and ⊥ to the grain) of samples of European (Metsa and Birch) plywood used in the UK. It also shows results of analyses of variance (single factor) at 95 % confidence level between parallel and perpendicular to the grain of the face veneers.

Table 5(a). Average MOR and MOE of European (7-ply metsa and 3-ply birch) plywood

Plywood Thickness (mm)		Modulus of rupture (Mpa)					Modulus of elasticity (MPa)				
		Avg MOR	St-dev	Min	Max	AN-OVA	Avg MOE	St-dev	Min.	Max.	AN-OVA
9.5 mm	//	78.79	3.22	65.2	84.1	SS	6886.47	334	6309	7720	SS
(Metsa)	⊥	89.97	8.17	68.4	106.7		9943.00	483	8800	10801	
8.5 mm	//	13.68	3.02	8.19	18.95	SS	722.82	149	451.3	976.6	SS
(Birch)	⊥	61.80	9.52	42.2	83.51		6983.99	724	5664	10096	

* NSS and SS stands for Not Statistically Significant and Statistically Significant

The European metsa plywood had the highest overall MOR (84 MPa) and MOE (8415 MPa). The European birch had the least overall MOR (37 MPa) and MOE (3853 MPa).

Table 5(b) also give the analyses of variance between MOR (// and ⊥ to the grain) of the European (Metsa and Birch) plywood. The results show that there are statistical differences between MOR (// and ⊥ to the grain) of European Metsa and Birch plywood.

Table 5(b). Analyses of variance between MOR of (// and ⊥ to grain) European plywood

		Metsa	
		//	⊥
Birch	//	SS	SS
	⊥	SS	SS

4.3 Bonding Quality

Table 6(a) give average shear strength and percentage wood failure of the specimens of the Kenyan and European plywood. European Metsa plywood had the highest average shear strength of 0.55 MPa with an average wood failure of 66 %. Apart from the 3 mm (3-ply) Kenyan plywood, the rest of the Kenyan plywood and European birch had an average shear strength and percentage wood failure of less than 0.2 MPa and 60 % respectively.

Table 6(a). Average shear strength and wood failure (%) for various plywood

Plywood thickness	Max. Shear Strength (Mpa)	Standard deviation	Minimum Value	Maximum Value	Wood Failure (%)
3 mm pine	0.21	0.06	0.15	0.31	76
9 mm pine	0.13	0.04	0.07	0.19	45
12 mm pine	0.18	0.03	0.14	0.23	59
17 mm pine	0.12	0.03	0.07	0.16	49
9.5 mm metsa	0.55	0.22	0.29	0.99	66
8.5 mm birch	0.14	0.03	0.09	0.18	51

The 17 mm (9-ply), 9 mm (5-ply) Kenyan plywood and the 8.5 mm (3-ply) European birch plywood had a maximum shear strength of less than 0.15 MPa and percentage wood failure of less than 50 %.

Table 6(b). Analyses of variance between bonding properties and various plywoods

	Plywood type	3	9	12	17	9.5	8.5
Shear strength (MPa)	3 mm, Pine	-	SS	NSS	SS	SS	SS
	9 mm, Pine	SS	-	SS	NSS	SS	NSS
	12 mm, Pine	NSS	SS	-	SS	SS	SS
	17 mm, Pine	SS	NSS	SS	-	SS	NSS
	9.5 mm, Metsa	SS	SS	SS	SS	-	SS
	8.5 mm, Birch	SS	NSS	SS	NSS	SS	-
Wood failure (%)	3 mm, Pine	-	SS	SS	SS	NSS	SS
	9 mm, Pine	SS	-	SS	NSS	SS	NSS
	12 mm, Pine	SS	SS	-	SS	NSS	NSS
	17 mm, Pine	SS	NSS	SS	-	SS	NSS
	9.5 mm, Metsa	NSS	SS	NSS	SS	-	SS
	8.5 mm, Birch	SS	NSS	NSS	NSS	SS	-

Table 6(b) also give analyses of variance (single-factor) at a 95 % confidence level between shear strength/wood failure and the Kenyan and the European plywood. It shows that there were statistical differences in shear strength between Metsa plywood manufactured in Finland and all thicknesses of Kenyan plywood. It was the same with European birch plywood.

CHAPTER 5

5.0 DISCUSSION OF RESULTS

5.1 Density

5.1.1 Kenyan plywood

The average densities (table 1) of the Kenyan plywood specimens are higher than the basic density at 12 % moisture content of the 30-year old Kenyan grown *P. radiata* (540 Kg/m^3) and *P. patula* (510 Kg/m^3) from where the plywood is manufactured (Gituiku, 1994).

This agrees with the fact that the density of plywood is slightly higher (usually by 5 - 15 %) than the density of the wood from which the plywood was made. This is because of the weight of adhesives and other additives and also because of compression of wood that occurs during the manufacturing processes (Haygreen and Bowyer, 1982 and BS EN 323, 1993).

5.1.2 European (Metsa and birch) plywood

The average density of the 9.5 mm (7-ply) European Metsa plywood was found to be much higher (about 37 %) than that of the 8.5 mm (3-ply) European birch plywood. One of the causes might be the use of thick, unequal plies and of different wood species for the construction of European birch plywood. European Metsa was constructed from uniform thin plies which is one factor that increases plywood mechanical properties (Sellers Jr., 1995).

5.2 Mechanical properties

5.2.1 Kenyan plywood

The overall average MOR and MOE of the Kenyan *P. Radiata* plywood specimens did not show a uniform pattern on the basis of the plywood thickness. The MOR and MOE decreased from the 3 mm (3-ply) to the 9 mm (5-ply) plywood and then increased slightly to the 12 mm (7-ply) plywood before decreasing again to 17 mm (9-ply) plywood.

An analysis of variance (two-factor, with replication) at 95 % confidence level indicated that there were statistical differences in MOR and MOE parallel and perpendicular to the grain of the face veneers for all plywood thicknesses except for the 12 mm plywood.

The average MOR and MOE parallel to the grain for Kenyan 3 mm, 3-ply plywood was exceptionally low compared to its corresponding MOR and MOE perpendicular to the grain of face veneer. This was also reflected in fig. 2 which shows scatter graphs for the 9 mm Kenyan plywood and the European 9.5 mm Metsa and 8.5 birch plywood.

5.2.2 European (metsa and birch) plywood

The overall average MOR and MOE of the European Metsa plywood was very high (about 50 % higher) compared to that of the European birch plywood. However, the average MOR and MOE parallel to the grain of the face veneer of the 8.5 mm (3-ply) plywood was also exceptionally low compared to that perpendicular to the grain of the face veneer.

European Metsa was constructed from uniform thin plies which is one factor that increases the mechanical properties plywood(Sellers Jr., 1995).

5.2.3 A comparison of Kenyan and European plywood

The average density of the 8.5 mm European birch was very low (490 Kg/m^3) compared to the Kenyan plywood. The lowest average density was found in the 3 mm (3-ply) plywood (580 Kg/m^3). However, the 9.5 mm European Metsa plywood had the highest density (770 Kg/m^3).

The average MOR and MOE of the plywood followed the trend of average density. The 9.5 mm European metsa plywood had the highest mechanical properties followed by the Kenyan plywood of all sizes. The 8.5 mm European birch had the least MOR and MOE. This was also shown in figure 1 when Kenyan and European plywood of the same size were compared.

The low average densities and MORs of the Kenyan and European plywood specimens could be due to several factors: for example the Kenyan plywood was constructed from veneer of unequal thickness. The European birch plywood was constructed using three thick plies which could result in plywood with low mechanical properties. On the other hand, the European metsa plywood was produced from veneer of equal and thin thickness.

Many researchers have also given several factors that could affect the quality of the mechanical properties of plywood. For example, veneer thickness and adhesive content and glue spread level (BRE, 1995).

It was deduced from Figure 1 that average MOR of plywood increases closely with average density. This agrees with findings by BRE (1995) and is also indicated by the high correlation coefficients in Table 7.

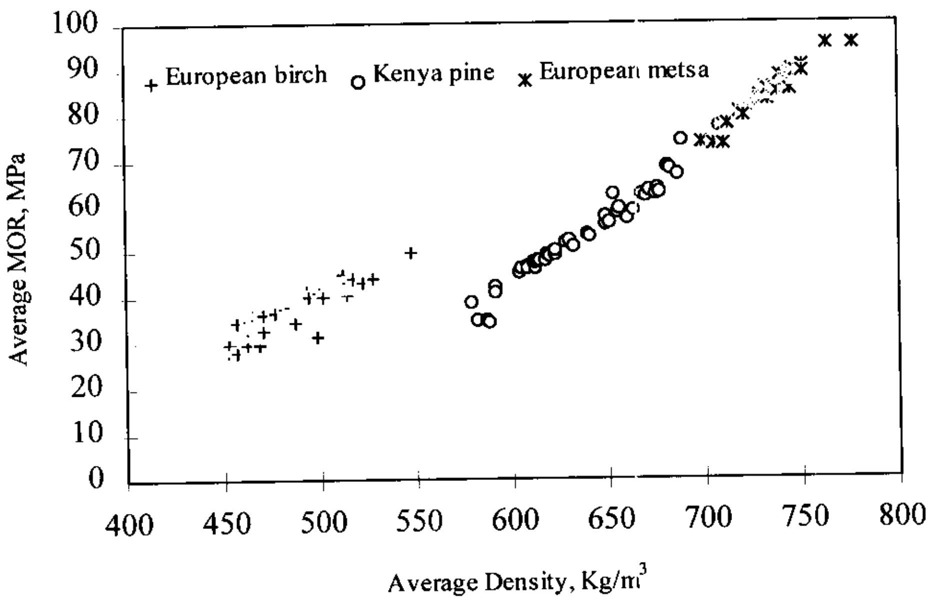


Fig.1. Relationship between density and MOR

The high correlation between density and MOR is a good indicator that density can be used as a predictor of MOR.

Table 7. Linear regression analysis between density and bending strength

Plywood type	b	c	R2
3 mm Kenyan	0.323	-114.05	0.58
9mm Kenyan	0.296	-134.61	0.96
12mm Kenyan	0.299	-135.30	0.95
17mm Kenyan	0.382	-200.66	0.96
9 mm European Birch	0.194	-57.05	0.76
9 mm European Metsa	0.317	-148.79	0.95

Regression type: Y = bX + c where Y = MOR, X = Density

5.2.4 Mode of failure in bending

Appendix V gives a general indication of the mode of failure in bending of 8.5 mm birch, 9.5 mm Metsa and 9 mm Pine plywood. Apart from the 8.5 mm Birch plywood which failed along the gluelines, 9.5 mm metsa and pine plywood failed by snapping. The mode of failure also suggested that the strength of 9.5 mm Metsa plywood was superior to the other two.

5.3 Bonding Quality

Apart from the 3 mm (3-ply) plywood, the rest of the Kenyan plywood and European birch plywood had very low average shear strengths which do not meet the bonding quality requirements for shear strength of $0.1 \le f_v \le 0.4$ MPa specified in BS EN 314-2 (1993). However, the 3 mm (3-ply) Kenyan plywood and European Metsa plywood met the first and second class of shear strength of $0.1 \le f_v \le 0.4$ MPa and $0.4 \le f_v \le 0.6$ MPa respectively of the European standard for plywood for interior use. The rest of the plywood did not meet either the mean shear strength or percentage wood failure required.

Poor adhesive wood-glue bond in plywood could be due to many factors. e.g. use of low quality peeler logs and hence veneer, use of veneer of ununiform thickness, yellow stain, improper veneer block treatment prior to peeling, growth characteristics and adhesive application method. Yellow stain particularly in pine changes veneer porosity and permeability as well as damaging veneer-drying surface. Heating freshly debarked peeler blocks in hot water vats prior to lathe cutting gives very smooth peeling. Uniform veneer thickness is important in obtaining:

- good adhesive-wood bonds
- uniform pressure during the pressing operation
- uniform spreads during roller coater adhesive application (Sellers, Jr., 1985).

Olivers (1981) enumerates other crucial factors that affect wood bond formation :

1. Wettability of wood fibres by adhesive. This depends on the moisture content of wood fibres, surface roughness and inherent attraction between wood and solvent
2. Application of pressure-laden veneers spreads and transfers viscous adhesive and causes bulk flow of adhesive solids and solvent through wood surface into large pores and capillaries in fibre walls, thus reducing thickness film
3. Cure of adhesive which involves solvent loss and chemical cross-linking. Increase of adhesive content decreases cross-linking, although each rate increases differently with temperature.

Most gluing parameters are affected by time, temperature, pressure and fibre properties so that adhesive can be manipulated properly to form good bond. The thermodynamic processes of wetting and adsorption cannot be manipulated easily. Moisture content is the most important wood property influencing bonding: it influences the rate of glueline heating and curing. At any specific wood moisture content, assembly time and the amount of adhesive must be adjusted for optimum bond quality. Density affects gluing; gluelines may vary in thickness because dense woods are more difficult for adhesives to penetrate and less conformable under pressure. Thick areas in glueline tend to be weaker. A broad range of densities within same pieces of wood may create bonds of different quality in close proximity (Olivers, 1981).

Other factors that could affect bonding quality include extractives, physical characteristics and chemicals composing veneer surface, construction of plywood from veneers of non-uniform thickness, use of very wet or very dry veneers and the incorporation of a long pre-pressing time which significantly reduce strength.

Extractives on veneer surface influence bonding by reducing wettability, inhibiting adhesive penetration, retarding or preventing adhesive cure or diluting adhesive solids. Glue spread also has significant effect on plywood bonding strength. Higher urea content in urea formaldehyde lowers bonding (Olivers, 1981; Suomi et al, 1986 and Sutigno, 1995).

An analysis of the relationship between percentage wood failure and shear strength shows that shear strength increases with percentage wood failure for all plywood types (Figure 2). It can be deduced from the figure that European Metsa plywood has superior shear strength and percentage wood failure than European birch and Kenyan pine plywood. European Metsa was constructed from plies of uniform thickness (unlike all the Kenyan plywood) and this could have contributed to its high shear strength.

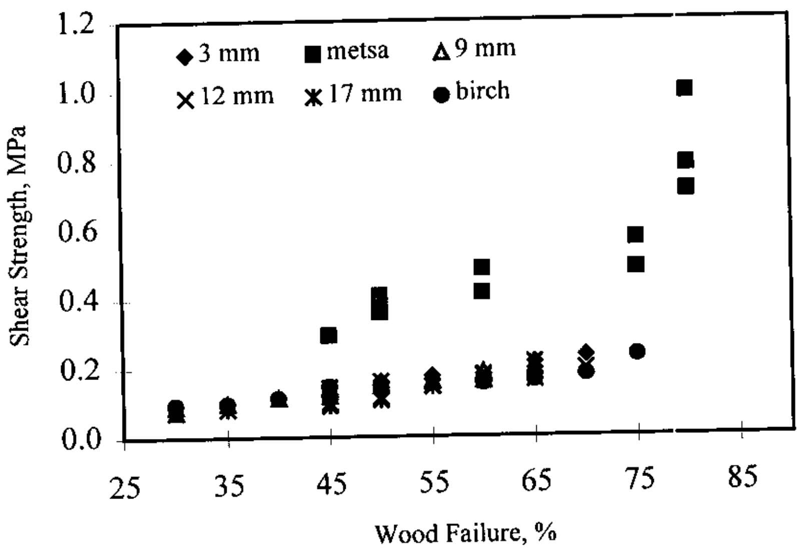


Fig. 2. Relationship between Wood Failure and Shear Strength

Table 6 also shows that there is strong correlation between percentage wood failure and shear strength. For all plywood types, the correlation coefficient (R^2) was very high. This indicates that wood failure in plywood can be used as a good predictor of shear strength.

Table 6. Linear regression analysis between shear strength and wood failure

Plywood type	b	c	R^2
3 mm	0.006	-0.275	0.78
9 mm	0.003	-0.011	0.94
12 mm	0.003	-0.003	0.83
17 mm	290.1	14.69	0.89
Metsa	0.013	-0.303	0.71
Birch	436.9	-0.275	0.92

Regression type: $Y = bX + c$ where Y = Shear strength, X = Wood failure

CHAPTER 6

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

a) Three thicknesses of the Kenyan *Pinus radiata*(9 mm (5-ply), 12 mm (7-ply) and 17 mm (9-ply)) and the European birch plywood failed to meet the bonding quality requirements of BS EN 310 (1995). Their shear strength was not within the $0.2 \leq f_v \leq 0.4$ MPa which is the minimum class specified by the standard.

b) European Metsa and 3 mm, 3-ply Kenyan plywood met the bonding quality requirements of BS EN 310 (1995). The shear strength of European Metsa and 3 mm, 3-ply Kenyan plywood was 0.55 MPa and 0.21 MPa which fall within $0.4 \leq f_v \leq 0.6$ MPa and $0.2 \leq f_v \leq 0.4$ MPa classes respectively.

c) European metsa had the highest average bending strength and stiffness in bending (84.38 MPa and 8414.74 MPa) followed by Kenyan pine (53.48 MPa and 5697.54 MPa) and then European birch (37.74 MPa and 3853.41 MPa) plywood when 9 mm, 5-ply plywood was compared.

6.2 Recommendations

a) Research work should be carried out on the Kenyan *P. Radiata* plywood to understand causes of its generally poor wood-adhesive performance. This would involve investigating the effect of veneer thickness, adhesive quantities and ratios, adhesive spreader and spread levels and pressure levels, pressing time and temperatures used.

b) Research work should be carried out on European birch to find out causes of its poor wood-adhesive performance and also why its bending strength parallel to the face grain is exceptionally low (although it is fairly high on the perpendicular face).

APPENDICES

Appendix I. Density parallel (//) and perpendicular (⊥) to face grain for Kenyan and European plywood

Specimen number	3 mm		9mm		12mm		17 mm		Metsa		Birch	
	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥	//	⊥
1	522.11	526.55	616.51	600.54	597.61	608.75	702.24	654.68	723.28	735.20	471.06	482.17
2	530.37	480.96	570.96	605.09	595.19	555.45	645.31	657.41	712.90	684.44	437.57	493.19
3	504.21	581.70	600.43	615.66	639.90	609.35	691.16	603.71	739.53	701.58	461.72	452.16
4	529.26	502.88	590.28	592.07	608.82	571.02	660.42	643.07	725.74	733.26	459.44	474.95
5	635.19	600.31	597.61	611.46	557.32	679.91	705.41	646.39	738.42	727.97	457.13	482.95
6	540.77	507.05	579.63	579.00	566.84	578.18	673.02	615.03	728.97	712.43	474.22	466.98
7	579.98	681.70	645.71	589.01	607.06	583.61	729.07	648.88	738.63	736.11	464.93	476.15
8	548.12	509.82	592.81	637.25	571.81	622.05	619.10	621.54	718.14	703.53	442.19	464.24
9	515.38	512.12	630.25	593.85	580.20	595.77	688.42	606.28	732.63	739.47	462.76	461.33
10	497.85	554.22	595.39	630.80	590.22	587.34	702.61	617.64	719.58	706.03	444.64	485.86
11	586.33	483.34	606.03	577.94	621.80	576.36	665.87	646.63	735.36	724.95	476.02	505.03
12	517.33	535.49	599.88	576.24	596.07	675.33	686.04	601.00	719.99	737.46	454.28	470.83
13	517.58	626.92	542.29	621.60	606.11	582.98	688.41	630.81	740.52	716.61	455.83	471.81
14	559.46	556.07	594.34	662.72	596.50	606.90	711.80	621.44	722.45	742.63	483.01	453.49
15	644.58	566.00	605.56	605.81	574.97	572.88	697.17	632.30	716.23	724.80	457.84	475.44
16	576.16	680.63	642.91	595.68	600.01	593.65	692.90	607.80	730.53	680.84	487.81	450.24
17	549.67	585.73	612.09	611.86	658.34	643.32	718.67	625.45	726.35	740.63	434.78	480.80
18	610.44	706.91	601.78	623.61	607.48	653.02	652.33	637.61	719.76	705.21	449.40	532.27
19	544.26	618.58	647.14	597.84	578.89	596.96	719.91	657.04	730.53	733.97	463.40	446.13
20	615.36	507.76	619.99	617.70	596.08	601.69	704.58	625.78	712.84	707.30	495.91	484.02
21	595.36	627.53	757.92	618.64	616.63	542.02	729.87	661.80	730.95	734.93	443.71	580.54
22	554.80	719.73	631.44	650.29	617.87	607.46	737.72	623.59	719.58	718.40	473.64	490.26
23	646.90	701.45	686.87	622.71	692.52	558.97	709.37	635.56	749.52	735.78	477.45	578.61
24	562.05	658.97	642.40	659.51	704.28	609.09	724.16	649.23	735.37	726.50	475.03	493.04
25	564.52	506.83	594.29	650.52	633.07	596.08	715.87	593.18	751.09	737.43	501.49	593.40
26	544.11	676.28	644.97	633.40	648.16	611.61	735.73	643.54	721.68	758.20	490.64	493.45
27	608.79	525.36	645.42	614.65	713.69	611.80	719.63	729.88	748.10	739.05	478.60	506.47
28	622.52	665.05	617.88	646.88	651.29	727.00	682.49	682.67	763.11	763.48	480.00	501.87
29	591.49	690.19	646.76	703.28	655.44	736.20	723.92	680.79	740.51	752.17	544.33	453.27
30	609.10	642.04	679.25	648.31	625.52	636.39	708.92	676.48	738.11	747.09	483.36	504.48
31			648.25	649.72	662.76	686.17	724.64	678.30	745.09	742.07	486.70	490.93
32			650.85	647.96	648.29	652.32	732.39	669.74	790.32	763.21	540.34	505.77
33			727.86	689.36	679.44	710.69	731.86	699.98	743.72	741.80	488.31	501.13
34			659.06	653.17	696.40	659.14			756.96	745.90	511.60	518.67
35			692.04	613.40	675.16	672.90			746.81	752.17	495.89	504.25
36			671.41	663.42	614.54	755.99			760.20	730.33	536.39	520.72
37			683.77	669.20	696.25	677.43			748.03	748.36	496.25	475.56
38			680.21	659.63	701.18	571.64			742.68	734.39	500.57	535.28
39			681.75	662.31	694.55	683.10			749.47	752.25	532.93	497.08
40			711.24	653.91	709.52	744.87			742.13	748.30	504.92	519.16
41			635.58	685.97	709.93	691.12			750.11	742.92	506.96	496.81
42			690.78	682.27	711.27	696.24			746.98	783.35	510.32	464.57
43			669.38	684.63	686.29	697.57			755.74	788.26		
44			703.58	659.34	593.87	624.26						
45			655.23	719.08	736.39	716.94						

Appendix II. Bending strength and stiffness in bending // and ⊥ to the grain for Kenyan and European plywood

Speci-men no	mor 3 //	moe 3 //	mor 3 ⊥	moe 3 mm ⊥	mor 9 mm //	moe 9 mm //	mor 9 ⊥	moe 9 mm ⊥	mor 12 //	moe 12 //	mor 12 ⊥	moe 12 ⊥
1	94.10	25.09	82.18	13785.48	52.57	5276.05	39.93	4275.45	47.22	4970.29	42.93	3725.6
2	96.63	25.77	51.85	2732.03	28.44	3544.58	41.09	5205.60	43.93	5174.33	33.25	3924.1
3	87.87	23.43	93.84	15961.60	49.12	6376.77	44.74	5202.21	58.18	4898.23	45.2	4492.9
4	94.21	25.12	67.43	4528.27	47.21	6149.13	37.45	3893.73	53.28	5528.09	34.13	3817.5
5	309.65	82.57	100.81	16681.42	48.85	4786.23	41.91	5448.03	29.61	3974.1	60.16	5658.1
6	97.03	25.87	69.64	4792.42	41.46	4300.45	35.87	4669.73	31.25	6567.52	36.36	4509.9
7	130.79	34.88	146.94	23072.47	60.04	5974.61	36.26	4802.92	50.89	3942.29	39.97	4033.1
8	106.36	28.36	80.81	5389.50	47.29	5440.98	48.80	4667.29	32.26	4518.39	48.79	7761.1
9	90.86	24.23	81.28	6094.14	53.87	4675.03	38.35	5071.45	37.33	4777.55	40.73	5505.4
10	72.15	19.24	86.50	13896.07	48.17	5315.38	47.81	5822.43	41.16	3576.91	40.32	3539.2
11	132.50	35.33	62.94	5775.76	50.71	6147.74	31.50	4225.66	55.96	5868.02	35.52	4508.8
12	91.17	24.31	85.35	6375.60	48.85	5974.03	20.45	3234.56	45.17	5802.61	58.28	8663.5
13	91.72	24.46	104.71	15671.81	24.78	3384.44	45.46	4266.15	50.57	5619.42	37.08	3950.5
14	110.35	29.43	86.89	6003.18	47.65	6595.13	56.18	4807.18	46.29	4644.85	41.59	4317.8
15	337.94	90.12	91.01	6065.77	50.65	6115.52	41.50	4532.30	37.21	4742.97	34.75	4381.9
16	118.19	31.52	136.18	20517.52	58.42	6704.83	39.11	4955.95	50.13	5218.67	40.66	4777.3
17	109.04	29.08	98.77	17064.13	52.09	6020.48	42.75	5543.68	61.95	5393.74	50.47	5468.9
18	214.59	57.22	163.99	23097.55	49.38	4028.03	46.15	4922.63	51.7	5405.84	56.02	5493.1
19	105.10	28.03	104.02	16394.54	60.85	6102.71	39.85	4833.78	37.33	4777.55	41.4	5223.9
20	303.78	81.01	76.72	4462.18	53.47	5348.32	44.97	3713.89	46.14	5709.02	41.56	4316.1
21	146.32	39.02	111.75	17650.09	103.20	10054.46	45.12	4808.49	53.95	5982.85	32.58	4386.4
22	109.27	29.14	164.11	24473.15	55.33	5677.81	50.83	5501.29	54.76	5551.62	42.66	3356.9
23	341.13	90.97	160.41	22649.33	71.98	7344.02	45.47	5084.92	67.36	5470	33.95	4553.3
24	112.06	29.88	118.46	18669.62	58.00	5934.01	54.70	6402.10	72.83	7764.1	43.43	5367.4
25	114.30	30.48	68.22	4917.04	47.55	5039.51	50.85	4581.51	57.46	5950.29	41.29	5624.1
26	97.86	26.10	133.71	22222.06	58.98	7907.63	48.56	5836.37	59.12	6323.34	46.83	5204.0
27	154.65	41.24	81.58	5884.41	60.01	5699.59	44.55	4049.19	87.32	8466.53	48.7	5728.9
28	305.34	81.42	125.87	18374.01	52.72	5841.72	49.27	4995.95	59.93	5260.39	85.89	9238.7
29	137.15	36.57	155.24	22709.71	60.47	5121.77	64.75	6276.15	60.07	5621.28	86.5	8788.4
30	206.35	55.03	117.97	19299.64	68.02	6273.63	49.89	4673.52	56.35	5239.4	50.06	5536.0
31	350.15	93.37	112.30	17954.67	61.70	6982.20	50.43	5315.26	64.56	5541.33	67.19	10023.
32	360.77	96.21	166.43	23212.01	65.46	5989.10	49.88	4709.07	59.13	5774.67	53.22	8912.9
33	371.23	98.99	167.28	23258.83	90.74	9943.31	63.65	5415.26	65.31	6137.97	84.54	10403.
34	393.69	104.98	170.66	23035.34	65.54	6961.25	52.82	5640.51	68.28	6159.28	57.67	8657.2
35	396.96	105.86	183.26	26958.10	81.28	9375.73	43.94	4909.63	64.56	5950.91	58.24	5351.6
36	429.78	114.61	206.80	24971.13	67.93	7477.39	56.87	4661.07	53.62	5706.92	93.01	9415.7
37					70.40	6247.29	57.00	5306.23	67.93	7668.77	59.8	5964.9
38					68.94	6328.06	54.86	5928.53	72.07	7006.46	34.35	3813.0
39					70.38	8255.20	55.95	5623.63	67.43	6599.82	61.49	8578.5
40					82.77	8868.27	53.48	5838.11	75.96	7931.96	90.57	8804.
41					55.65	6243.65	58.81	6146.44	80.46	7534.98	74.01	9106.2
42					75.88	8540.50	57.42	5796.78	86.99	8020	77.95	8571.4
43					67.27	6210.41	58.80	5841.15	65.41	7079.45	84.12	8604.4
44					82.54	8651.05	54.50	5233.43	43.91	5136.46	49.98	4790.6
45					65.48	5779.08					84.73	8926.2

Appendix II continued

mor 17 mm //	moe 17 mm //	mor 17 mm ⊥	moe 17 mm ⊥	mor birch //	moe birch //	mor birch ⊥	moe birch pp	mor metsa //	moe metsa //	mor metsa ⊥	moe metsa ⊥
63.19	8205.05	51.69	5435.22	187.02	12.47	60.81	7024.76	77.09	7139.07	90.19	9285.76
41.34	5781.43	53.71	6050.05	124.93	8.33	63.85	7337.69	74.42	6449.86	72.83	9722.94
57.83	8046.9	36.99	4969.79	168.31	11.22	44.30	6985.19	79.27	6662.73	78.92	9988.18
43.34	6478.68	46.56	5065.68	165.58	11.04	59.52	6542.21	77.17	6693.68	88.62	9850.51
63.52	8093.84	49.42	5391.78	159.03	10.60	61.34	6692.72	78.79	6490.49	87.18	10047.2
50.54	7811.2	37.57	4485.31	189.98	12.67	52.99	6659.14	77.41	7245.91	81.73	10214
75.32	10364.7	50.43	5920.22	184.69	12.31	60.14	7468.37	79.18	6824.14	91.21	9591.36
36.89	5936.4	41.45	5287.59	125.72	8.38	51.21	6066.64	75.75	6656.76	79.05	9973.12
56.91	5538.26	37.07	4719.48	173.30	11.55	47.61	6671.40	78.42	7020.67	93.17	10604.3
63.28	7925.28	40.12	4485.52	138.15	9.21	61.75	6411.91	75.84	6627.57	80.02	10446.7
44.44	6447.35	49.89	6073.52	202.77	13.52	68.92	7436.72	78.44	6309.43	86.69	8800.24
54.5	7487.11	36.12	5022.2	141.93	9.46	56.71	6899.39	76.44	6588.61	91.64	10216.2
56.41	6773.97	43.16	4666.88	154.71	10.31	59.46	6494.98	79.39	6783.80	83.73	9355.92
67.72	9083.72	41.12	5163.55	212.40	14.16	45.72	7184.66	77.04	6899.09	94.16	10208
61	6743.64	44.53	5254.56	163.33	10.89	59.76	6416.92	74.60	6488.15	85.13	10525
60	7425.6	37.2	4772.5	229.88	15.33	44.00	6900.98	78.11	7720.70	68.46	9093.2
68.19	6913.07	42.25	5181.12	122.89	8.19	60.80	6688.34	77.36	6844.21	93.21	10428.7
43.06	5391.62	46.25	5231.63	140.65	9.38	71.74	6401.36	76.17	6535.42	79.83	9648.75
69.97	8206.31	52.03	4544.17	182.76	12.18	42.24	5800.31	77.53	7237.24	88.92	9372.06
63.38	6364.14	42.98	5341.78	233.64	15.58	61.66	6686.16	65.22	6440.54	81.2	9577.78
76.88	7705.39	53.89	5988.48	131.86	8.79	80.98	10096.69	78.35	6688.64	90.17	9541.63
81.83	9331.61	42.23	4709.4	188.13	12.54	62.24	7588.20	75.80	6743.98	84.81	9281.24
67.5	7306.75	45.63	5152.92	205.55	13.70	72.43	7514.23	80.82	6638.21	90.48	9592.15
74.03	8569.51	51.4	5805.78	194.94	13.00	63.02	7013.24	78.47	6742.39	87.09	9764.5
68.15	8288.08	35.46	4786.43	239.61	15.97	83.51	8241.03	82.07	7188.71	91.34	9487.46
81.23	8778.95	47.19	5155.89	232.64	15.51	63.89	7044.30	76.65	7006.20	100.18	10538.4
69.71	7664.04			206.50	13.77	69.34	7170.54	80.66	6944.32	93.09	10494.2
54.18	7828.84			207.49	13.83	65.21	6989.33	83.28	7601.05	106.79	10564.5
71.08	7382.58			262.26	17.48	45.22	5835.19	79.36	6606.18	99.34	10564
65.67	6997.8			221.60	14.77	68.60	7564.42	78.56	7333.56	95.18	10012.7
74.62	7764.48			224.49	14.97	62.37	6420.56	79.97	6972.24	93.94	10034.2
80.4	8780.11			258.69	17.25	69.00	7413.68	83.91	7508.79	106.77	10801.1
77.15	8523.69			230.81	15.39	64.70	7195.10	79.90	6755.36	93.48	10614.5
				252.49	16.83	69.61	7277.77	82.80	7017.61	95.03	9277.2
				233.37	15.56	66.22	7520.10	80.05	6853.48	98.26	10003.1
				253.51	16.90	71.67	6769.80	82.98	7665.12	87.63	9593.55
				235.75	15.72	60.01	7128.41	80.49	6968.43	97.63	10108
				239.06	15.94	71.96	7169.50	79.67	6883.75	89.7	9973.79
				252.76	16.85	64.21	6467.79	80.66	6925.33	100.04	10080.5
				240.58	16.04	70.25	7274.40	79.62	6646.20	97.49	10196.1
				245.07	16.34	64.01	7198.92	81.70	7063.39	94.53	10190.5
				245.71	16.38	52.71	5664.64	80.46	6602.35		
								82.72	6871.24		

Appendix III. Average shear strength and wood failure (%) of Kenyan and European plywood

Table 1. Average shear strength of 3 mm Kenyan pine plywood

Specimen No.	Shear strength MPa	Wood Failure %
1	0.171	75
2	0.154	65
3	0.313	85
4	0.171	65
5	0.202	80
6	0.185	75
7	0.218	80
8	0.315	90
9	0.171	70
10	0.187	75
Mean	**0.21**	**76**
Stdev	**0.06**	**8.10**
Min.	**0.15**	**65**
Max.	**0.31**	**90**

Table 2. Average shear strength of 9 mm Kenyan pine plywood

Specimen No.	Shear strength MPa	Wood Failure %
1	0.089	30
2	0.097	35
3	0.073	30
4	0.112	40
5	0.117	45
6	0.137	45
7	0.146	50
8	0.160	55
9	0.160	60
10	0.186	60
Mean	**0.13**	**45**
Stdev	**0.04**	**11.3**
Min.	**0.07**	**30**
Max.	**0.19**	**60**

Table 3. Average shear strength of 12 mm Kenyan pine plywood

Specimen No.	Shear strength MPa	Wood failure %
1	0.179	60
2	0.194	65
3	0.175	55
4	0.143	45
5	0.162	60
6	0.160	50
7	0.214	65
8	0.233	70
9	0.195	65
10	0.155	50
Mean	**0.18**	**59**
Stdev	**0.03**	**8.18**
Min.	**0.14**	**45**
Max.	**0.23**	**70**

Table 4. Average shear strength of 17 mm Kenyan pine plywood

Specimen No.	Shear strength MPa	Wood Failure %
1	0.073	30
2	0.081	35
3	0.089	45
4	0.098	45
5	0.112	50
6	0.106	50
7	0.144	55
8	0.159	60
9	0.160	60
10	0.143	55
Mean	**0.12**	**49**
Stdev	**0.03**	**10.0**
Min.	**0.07**	**30**
Max.	**0.16**	**60**

Table 5. Average shear strength of 9 mm European Metsa plywood

Specimen No.	Shear strength MPa	Wood failure %
1	0.989	80
2	0.294	45
3	0.359	50
4	0.408	50
5	0.781	80
6	0.485	75
7	0.706	80
8	0.484	60
9	0.414	60
10	0.569	75
Mean	**0.55**	**66**
Stdev	**0.22**	**14.0**
Min.	**0.29**	**45**
Max.	**0.99**	**80**

Table 6. Average shear strength of 9 mm European birch plywood

Specimen No.	Shear strength MPa	Wood failure %
1	0.162	65
2	0.094	30
3	0.097	35
4	0.113	40
5	0.120	45
6	0.153	60
7	0.147	50
8	0.173	65
9	0.146	45
10	0.178	70
Mean	**0.14**	**51**
Stdev	**0.03**	**13.8**
Min.	**0.09**	**30**
Max.	**0.18**	**70**

Appendix IV(a). Analysis of variance for Kenyan plywood - density

3mm	567.47 //
	592.45 ⊥
9mm	656.49 //
	631.47 ⊥
12mm	647.50 //
	646.68 ⊥
17mm	592.45 //
	643.19 ⊥

Anova: Two-Factor With Replication

SUMMARY	567.47	Total
Count	2	2
Sum	1248.94	1248.94
Average	624.47	624.47
Variance	2050.561	2050.561
Count	2	2
Sum	1278.97	1278.97
Average	639.485	639.485
Variance	128.4804	128.4804
Count	2	2
Sum	1239.13	1239.13
Average	619.565	619.565
Variance	1470.446	1470.446
Total		
Count	6	
Sum	3767.04	
Average	627.84	
Variance	816.073	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F c*
Sample	-1182334	2	-591167	-971.918	#NUM!	5.14
Columns	0	1	0	0	1	5.98
Interaction	1182765	2	591382.3	972.2718	2.91E-08	5.14
Within	3649.488	6	608.2479			
Total	4080.365	11				

Appendix IV(b). Analysis of variance (ANOVA) between board density (Kg/m³) // to face grain for 9 mm Kenyan plywood

1	2	3
579.63	669.38	686.87
600.43	617.88	630.25
648.25	727.86	711.24
671.41	599.88	757.92
592.81	594.29	645.71
594.34	646.76	703.58
659.06	647.14	768.46
606.03	642.91	683.77
590.28	616.51	690.78
542.29	655.23	679.25
619.99	612.09	692.04
597.61	644.97	680.21
601.78	605.56	631.44
595.39	642.40	681.75
570.96	635.58	650.85

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	15	9070.2	604.7	1130.0
Column 2	15	9558.4	637.2	1111.5
Column 3	15	10294.1	686.3	157320

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	[illegible]
Between Groups	50608.02	2	25304.0	19.9	8.32E-07	
Within Groups	53402.03	42	1271.5			
Total	104010	44				

Appendix IV(c). ANOVA between MOR and MOE // and ⊥ to the grain face for 3 mm Kenya plywood

MOR (MPa)//	MOR (MPa) ⊥	MOE (Mpa)//	MOE (Mpa) ⊥
81.01	146.94	11944.53	23072.47
90.97	160.41	12055.05	22649.33
82.57	164.11	9218.71	24473.15
96.21	166.43	10008.82	23212.01
104.98	136.18	11775.38	20517.52
81.42	170.66	10555.12	23035.34
114.61	163.99	15045.29	23097.55
98.99	206.80	15350.76	24971.13
93.37	155.24	12858.75	22709.71
90.12	167.28	16398.89	23258.83
105.86	183.26	18187.41	26958.10
57.22	133.71	1200.04	22222.06
28.03	82.18	1311.61	13785.48
25.09	104.02	1201.37	16394.54
29.88	100.81	1237.53	16681.42
24.31	104.71	1122.62	15671.81
25.87	125.87	1161.72	18374.01
28.36	118.46	1307.11	18669.62
19.24	93.84	915.40	15961.60
23.43	111.75	1106.98	17650.09
26.10	117.97	1134.55	19299.64
25.12	112.30	1067.79	17954.67
29.43	98.77	1179.42	17064.13
30.48	86.50	1290.33	13896.07
25.77	80.81	1030.40	5389.50
24.46	85.35	933.94	6375.60
36.57	51.85	1624.34	2732.03
39.02	76.72	1631.42	4462.18
35.33	86.89	1666.46	6003.18
29.08	81.58	1186.40	5884.41
41.24	91.01	3554.36	6065.77
55.03	62.94	5170.54	5775.76
31.52	81.28	1455.14	6094.14
24.23	69.64	1097.25	4792.42
29.14	67.43	1285.58	4528.27
34.88	68.22	1419.40	4917.04

Anova: Single Factor (MOR)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	36	1818.94	50.526	968.6
Column 2	36	4115.91	114.33	1582.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	73278.77	1	73278.8	57.44	1.08E-1(
Within Groups	89287.48	70	1275.54		
Total	162566.2	71			

Anova: Single Factor (MOE)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	36	180690	5019.18	3E+07
Column 2	36	544600	15127.8	6E+07

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	1.84E+09	1	1.8E+09	40.154	1.97E-0
Within Groups	3.21E+09	70	4.6E+07		
Total	5.05E+09	71			

Appendix IV(d). ANOVA between 4 Kenyan plywood sizes for average density

3 mm	9 mm	12 mm	17 mm
638.00	597.14	602.22	677.36
611.74	598.05	630.01	660.80
640.71	620.16	620.26	672.00
650.12	662.66	635.11	683.74
632.28	613.10	631.45	667.47
621.14	639.48	617.84	683.61
626.22	660.89	590.45	678.92
668.55	614.37	588.18	673.36
675.75	654.68	590.29	676.02
646.07	602.85	602.93	673.04
653.03	639.81	601.57	685.27
566.98	622.24	584.31	732.81
529.22	625.05	623.09	696.02
604.55	605.53	600.32	670.60
597.42	597.28	587.79	694.68
584.32	641.39	691.93	696.44
574.82	603.45	690.86	657.55
578.75	660.86	703.09	664.40
518.51	589.44	697.19	664.44
528.97	622.40	699.93	676.73
499.27	626.28	686.39	648.70
521.25	612.54	710.02	653.55
538.11	620.37	673.28	653.16
525.58	608.52	690.55	662.92
519.07	657.37	685.87	687.70
559.06	649.03	706.59	637.01
500.36	663.62	707.82	674.28
521.35	661.32	702.62	663.23
562.98	652.36	611.15	662.46

Anova: Single Factor

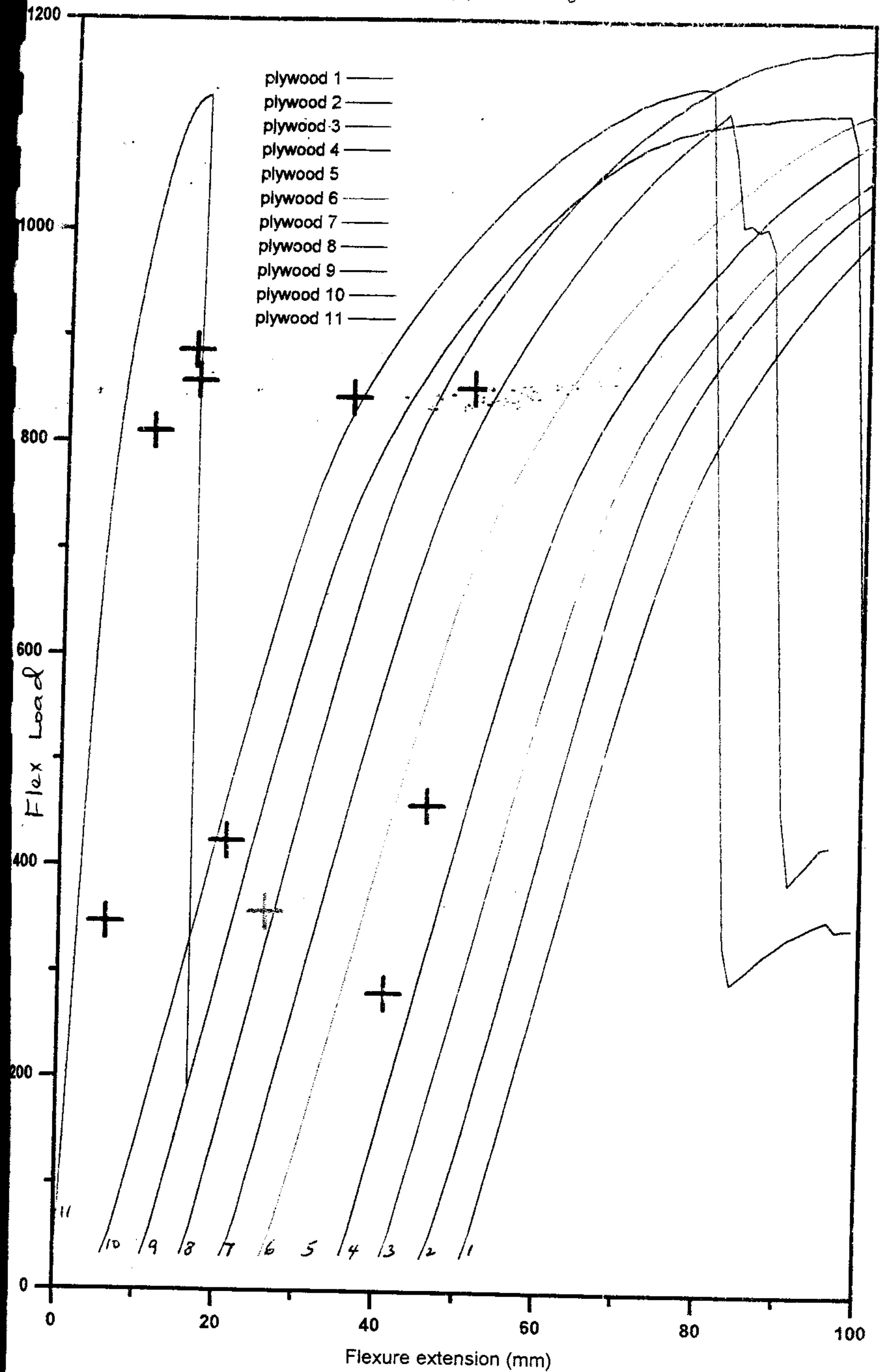
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	29	16894	582.6	3037.5
Column 2	29	18222	628.4	572.9
Column 3	29	18763	647.0	2213.1
Column 4	29	19528	673.4	333.3

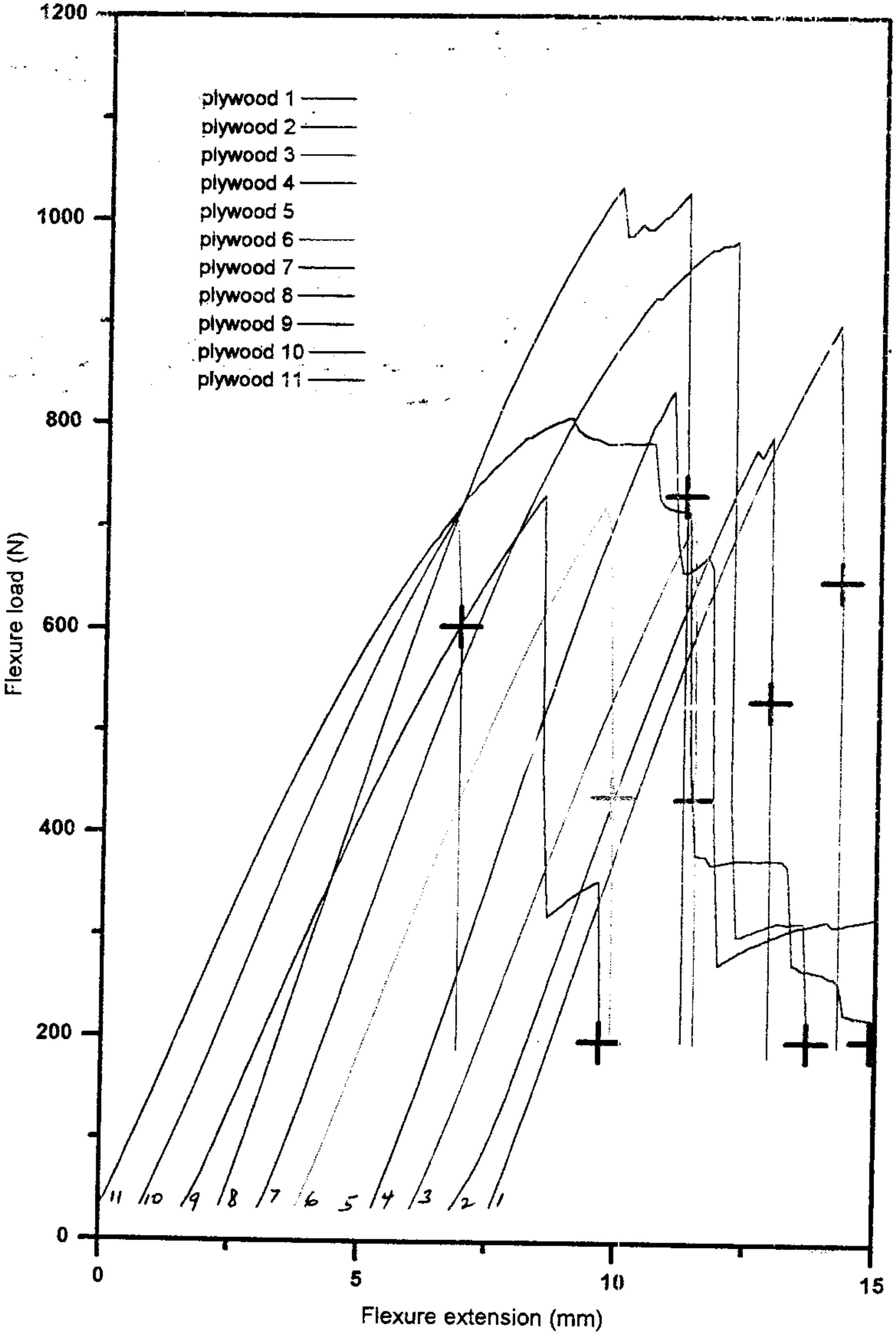
ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F cri*
Between Groups	127405	3	42468	27.6	1.95E-13	2.(
Within Groups	172387	112	1539			
Total	299793	115				

Appendix V(b). Flex Test for 9 mm metsa plywood // to grain



Appendix V(c). Flex Test for 9 mm pine plywood // to grain



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