THE ANATOMICAL STRUCTURES
OF SOME EGYPTIAN HARDWOODS AND
THEIR RELATION TO MECHANICAL PROPERTIES

by

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Abstract

The relationships between the anatomical structure and the mechanical properties were investigated for Z. chilensis, L. enicocarpa, L. ovata, L. kotschyi, L. fendleri, Z. birrea, Z. africana, and Z. papuana. These eight species were characterized anatomically using stereological techniques. Transverse sections of these woods as well as isolated fibers were projected on a grid, and point fraction or volume proportion for different types of cells, intersection counts, and number density count were made. Structural parameters were obtained from the stereological data. These parameters were the average volume proportion for different types of cells, the average cell wall and lumen fractions, cross-sectional dimensions for cells, fiber length, and ratios of cell dimensions.

The mechanical properties of the eight species were determined. These were compression strength parallel to the grain, hardness, and shear stress. The specific gravity was also determined for each species. The mechanical properties were then related to the
anatomical parameters using correlation and regression analysis.

The most important structural parameters influencing the mechanical properties of wood were found to be the average volume proportion for cell wall material which influenced all mechanical properties of wood with high and positive correlation coefficients. The specific gravity was also found to be influenced by the average volume proportion for cell wall material and the average volume proportion for fibers (positively). It was also found positively correlated with the average volume proportion for rays and average fiber length.

Compression strength was found to be highly and positively correlated with the average volume proportion for total cell wall material and average fiber length and negatively correlated with average fiber diameter. It was also found to be influenced by other factors such as the amount of extraneous material present in the wood as found in previous studies.
Hardness and shear stresses were found to be highly and negatively correlated with the average volume proportion for vessels, average fiber length, and average fiber diameter. It was also found that both hardness and shear stresses were positively correlated with the average volume proportion for fibers.

The regression models obtained relating anatomical properties to mechanical properties of wood may be useful in predicting mechanical properties of wood.
INTRODUCTION

Wood has been a pre-eminent construction material since times immemorial. Its availability in various forms and sizes, its relative ease of working and such properties as relatively great strength with respect to its weight, have made it an essential material for human survival. Wood is a renewable natural resource unlike other competing construction materials such as steel, aluminium, and concrete.

Wood has been used for shelter, fuel, weapons, and tools since prehistoric times. As technology developed, wood came to be used for boats, telephones and telegraph poles, railway sleepers and bridges. Wood is also used extensively in combination with other materials such as in railway carriages, aircrafts, engineering and construction works.

Today, in spite of the availability of numerous new synthetic materials, wood products are still dominating the higher level of economic development. Wood plays an important role in the development of nations because it is one of the major sources of fuel and because of its renewability and versatility. Then wood is used in
construction, containers, etc. It offers the greatest opportunity to the designer and user due to the fact that wood can be cut and worked into various shapes with power-driven machinery. Wood can be joined with nails, screws, bolts, connectors, and adhesives, producing strong joints. Wood can be designed to carry impact loads that are twice as great as those it can sustain under static loading (Fahsion 1936). This can be contrasted with steel and concrete for which no increase in load is allowed under similar conditions.

Wood is significantly different from all other construction materials in that it is a product of a complex biological system, the tree, and as such it has highly variable properties which depend upon its structural characteristics. During the years wood anatomists provided the basic information on dimensional parameters of wood and used the anatomical structure as a principle of wood identification. Recently quantitative characterization is used in the study of structure-property relationships. This study is an attempt to proceed along these lines and aims
at the following objectives:

1- Investigation of the microstructural characteristics of eight Sudanese hardwoods using micromorphological techniques.

2- Deposition of some physical and mechanical properties of these woods.

3- To seek any interrelationships between anatomical and mechanical properties of wood.

In the past people were reluctant to use Sudanese woods and preferred imported hardwoods because of their ease of work. For the establishment of the wood technology section of the Forest Research Centre at 1963 so many people started using local timber because many problems of wood utilization were solved and a lot of information relating to wood properties had been provided (Mawrouk, 1979).

The existing forests of the Sudan are capable of producing all our requirements of timber and timber products if managed properly.
The forests of the Sudan cover about 31% of the total area of the country (Belle, 1979). There are appreciable resources of timber in the natural stands of different geographical regions of the Sudan. These are great opportunities for growing a wide range of species to meet the increasing demand for timber and other wood-based products. The establishment of an integrated forest industry will enable these regions with large local resources to expand the use of timber and those with small local resources to use them more efficiently.
Since the 17th century, only a few attempts of quantifying anatomical structure of wood were documented in the literature. Most of the work in the past was done on coniferous woods that have simple microscopic structure unlike hardwoods which have complicated anatomical structures. Softwoods possess only a few types of cells of uniform arrangement that gives the appearance of simple structure. Only two types occur in softwoods, these are:

1. Tracheids which comprise over 90% of the volume of softwoods.

2. Parenchyma cells.

The longitudinal elements of softwoods contain:
1. longitudinal tracheids and strand tracheids.
2. longitudinal parenchyma and epithelial cells.

The transverse elements contain:
1. Ray tracheids.
2. Ray parenchyma and epithelial cells.

Hardwoods show more variation in size, shape, and arrangement within a growth ring.
The longitudinal elements of hardwoods contain:

1. Vessels
2. Tracheids
3. Fibers
4. Longitudinal parenchyma

**Vessels:**
Vessels are tubelike structures of indeterminate length. They are composed of a number of cells called vessel elements, vessel members, or vessel segments. Each vessel element develops from a longitudinal cell that has arisen through the division of a fusiform cambial initial. Vessel members have bordered pits and their inner surfaces may possess spiral thickenings. The area of the adjacent end walls involved in endwise connection of two vessel members is called perforation plate. Perforation may be simple or multiple. Simple perforation is a single, usually large, more or less rounded opening, while multiple perforation indicates two or more openings. In certain species, multiple perforation plates consist of elements parallel
openings separated by bars, these plates are called scalariform i.e. ladder-like. In cross section vessels appear as solitary pores, or in multiples, chains, or clusters, and their shapes may be drum-like or barrel-shape to oblong and linear with or without tail-like extensions at one or both ends. The vessel extensions i.e., the parts of the vessel extending beyond the perforations, may vary from a short or long slender tail to a strip-like (ligulate) end, or may have a broad taper. Vessel extensions are readily visible only when the cells have been separated by maceration. Panshin and de Zeeuw (1980) classified the arrangement of vessel elements into three groups on the basis of variation in pore size within growth rings. If the pores in the springwood are much larger than those formed later in the season, the wood is ring-porous, as in Oak (Quercus spp.). On the other hand if the pores are fairly uniform and quite evenly distributed throughout the ring, the wood is said to be diffuse-porous, as in Birch (Betula spp.). Certain woods such as Juglans spp. and Diospyros spp. are intermediate in this respect.
and are classified as semi-ringed or semi-diffuse-porous.

The inclusions which are most frequent in vessel elements are tyloses and various amorphous substances that are gummy, resinous, or chalky in nature.

**Hardwood tracheids:**

There are two distinct types of hardwood tracheids. These types are vascular tracheids and vasicentric tracheids. Vascular tracheids are cells very similar in size, shape, and position to small late-wood vessel elements, except they are imperforate at the ends. They are arranged in vertical series like the small vessels with which they are associated. The lateral walls of vascular tracheids contain numerous bordered pits of the same general type as intervessel pits, and frequently possess conspicuous spiral thickenings. Vasicentric tracheids are short, irregularly shaped cells, with closed ends. Vasicentric tracheids generally differ from vascular tracheids in having tapering or...
rounded ends and in not being arranged in definite longitudinal rows.

Fibers:

Fibers are long narrow cells with closed ends. They have average length ranging from 1.0 to 2.5 mm and diameters ranging between 0.01 to 0.09 mm. (Pascal 1959). Fibers have closed ends mostly pointed and sometimes forked or equipped with dentations. The proportion of fibers is variable in different species of hardwoods. The walls of fibers may be thick or thin and also the lumina may be narrow or large according to the species.

Fibers are classified into fiber tracheids and libriform fibers according to the nature of pitting. Fiber tracheids have bordered pits, while libriform fibers have simple pits. Libriform fibers are usually smaller than fiber tracheids in length and diameter, and have narrow lumina that are often difficult to see under low magnifications. Fiber tracheids and libriform fibers may occur in the same wood, and the transition between them is often so gradual that it may be an arbitrary matter in assigning a given cell to one or
the other type. The primary function of fibers is to support the living tree and sometimes they participate in conduction especially fiber tracheids. Some fibers are septate, i.e., with thin transverse walls across the lumens as in Safal (Roswellia parviflora). Gottwald (1971) found that tyloses occur in the fibers of several genera of the Magnoliaceae. In tension wood of hardwoods gelatinous fibers mixed with unmodified fibers are mostly found. Gelatinous fibers differ from the normal fibers in possessing an innermost cell wall layer which differs in physical and chemical properties from the usual secondary cell wall layer. This layer generally described as gelatinous, is highly refractory to light and usually gives a cellulose reaction with various staining reagents indicating absence or a low degree of lignification (Panshin, 1980).
Parenchyma:

These are short brick-like thin-walled cells with thin simple pits. Their average length is between 0.1 - 0.2mm, and their width is between 0.01 - 0.02mm. Parenchyma cells are classified as vertical or axial parenchyma and radial or ray parenchyma. Axial parenchyma is more abundant in hardwoods than in softwoods. There are three kinds of longitudinal parenchyma cells: (a) strand parenchyma, (b) fusiform parenchyma, and (c) epithelial parenchyma.

(a) Strand parenchyma is formed through the transverse division of the fusiform cambial daughter cell, with the entire strand approximately the same shape as the original cambial cell. Strand parenchyma is by far the most common type of longitudinal parenchyma in hardwoods. The descriptive terms used in defining different arrangements of longitudinal parenchyma as visible in transverse sections, are as follows:
1. Apotracheal parenchyma:
   These are longitudinal parenchyma cells arranged independently of fibers.
   a. Diffuse-apotracheal: These are single parenchyma cells distributed irregularly among fibers.
   b. Diffuse-in-aggregates: These are apotracheal parenchyma grouped in short tangential lines.

2. Paratracheal parenchyma:
   These are longitudinal parenchyma associated with vessels or vascular tracheids.
   a. Scanty paratracheal: These are paratracheal parenchyma confined to a few cells around the vessel.
   b. Vasiticentric paratracheal: These are paratracheal parenchyma forming a more or less complete sheath, one or more cell wide around a vessel.
   c. Aliform paratracheal: These are paratracheal parenchyma with ring-like lateral extensions.
   d. Coincident paratracheal: These are aliform parenchyma forming irregular tangential or diagonal bands that coalesce.
3. Banded parenchyma:

These are parenchyma cells forming concentric lines or bands.

4. Marginal parenchyma:

These are longitudinal parenchyma cells occurring either as occasional cells, or forming a more or less continuous layer of one to more cells in width at a margin of a growth ring.

Ray parenchyma constitute wholly or in part the rays. In hardwoods, rays are composed of ray parenchyma only, whereas in softwoods, ray tracheids may also be present, as may resin canals. Rays may be uniseriate, biseriate, or triseriate, and aggregately.

In some species, the rays are arranged in horizontal series as seen in tangential sections. Such stratified arrangement of rays is known as storied rays. Average ray volume ranges from about 5 per cent to 20 per cent in hardwoods and from about 9 to 20 per cent of the total volume of wood in softwoods.

Structural differences among woods lead to differences in physical and mechanical properties of wood. (End of page 155.)
Physical properties of a material depend on the properties of its parts or structural elements. It has been shown by investigation that property differences are closely related to the structure at the microscopic level (Tifju, 1969; Kellogg and Tifju, 1962). Thus the utility of a piece of wood for a specific application is dependent upon its properties, which in turn are influenced by its structural characteristics. Next characterization based on anatomical structure serves as a principal method of wood identification (Panahia & De Gaeuw, 1970).

Since wood anatomy and identification involve the recognition of shapes, sizes, and distribution of elements or features, it is therefore surprising that wood anatomy has only occasionally been subjected to the methods of quantitative microscopy. In the meantime so many of sciences have developed sophisticated mathematical methods to quantify the structure of their respective materials. For example, notable advances have occurred in medical science (Elias et al., 1971; Weibel and Bolender, 1973) where
changes in cellular structure have been related to various illnesses. Metallographists have been for some time interested in particle shape and size distribution for crystals and phases in alloys (Beckoff, 1967; Glisson and Woodhead, 1960; Hillert, 1966).

**Stereo**

Stereoology may be defined as a body of methods for relating the microstructure as seen in the thin section or projection plane to the true spatial quantities. It means in a broad sense, the study of structure in three dimensions. Thus, it includes the narrower and more restrictive terms, such as stereometry (measurement in three dimensions), and morphology (the study of shape).

The term stereoology was coined at the foundation meeting of the International Society for Stereoology (ISS) in 1961. The founder and first president of the (ISS), Hans Sjövall, has proposed the following definition: "Stereoology, sensu stricto, deals with a body of methods for the exploration of three-dimensional space, when only two-dimensional sections through solid bodies or
Their projections on a surface are available. Thus stereology could also be called extrapolation from two to three dimensional space (Eljasz, 1976).

The use of stereology:

Stereological methods were used to evaluate different characteristics and to avoid the disadvantages of the manual methods which are time-consuming and have the probability of increasing error. Metallurgists are applying stereological principles to study the composition of metal alloys, the size distribution of grains and particles, the contact surface area between phases and the anisotropy of grains, i.e., microstructural properties which are related to physical and mechanical properties of materials. Also stereology is used in mineralogy, petrography, and geology. In these fields many of the foundations of basic stereological principles have been laid, starting in 1947 with the fundamental principal of Delissee who demonstrated that the volume fraction of
rocks can be directly estimated from the real profile fraction of the section. In biology and medicine the internal structure of cells, tissues, and organs is now being quantitatively investigated in many fields of stereology. Stereology also provides insights into the internal geometrical properties of living organisms, such data can be successfully applied to quantitative correlations between structure and function applications that have previously been virtually impossible. Characterization of the microstructure of seven Sudanese hardwoods was done (Woolson 1978) using the principles of stereology to relate the structural properties of wood to paper-making properties. Also quantitative characterization of the microstructure of 22 Brazilian tropical hardwoods was done using stereological methods to compare structure with compression and bending strength of the wood. Stereological measurements are mostly statistical in nature and where these methods are applied, there must be an underlying assumption that the subject material presents an extended system of effectively
repetitive structure (Schoof and Rhodes, 1963).

Point counting ($p_p$) is one of the simplest operations of stereology. It refers to the number of features on a particular structure as a proportion of the total number of test points. These test points could be the intersections of test grid or the end points of test lines on a grid as shown in Figure (1). Each point count represents a random statistic which is an unbiased estimator of the area fraction ($A_p$) and the volume fraction ($V_p$).

Intercept count ($E_L$) refers to the number of points of intersection with boundaries generated per unit length of test lines. A linear or circular test array is added randomly to the microstructure plane. It is a count of the number of times that line segments intercept cell boundary when divided by the actual total segment length gives the number of intercepts per unit length. This measurement is an unbiased statistical estimator of half the surface.
Figure 1:
Examples of typical point-counting grids:
(a) 16-point square grid (b) and points grid (c) random points grid.
area per unit volume. The actual total grid length (r) depends on the magnification of the microstructure but its value can be determined at standard magnification. Another scheme for determining \( \bar{N} \) utilizes a single test line of fixed length, which is not drawn randomly or uniformly over the microstructure.

\( \bar{N} \) is another measurement similar to \( \bar{N} \) and defined as the number of interceptions of features of the microstructure (rather than true points) per unit length of the test lines.

\( \bar{N} \) is another measurement which refers to the number of objects or features in a certain area of the microstructure.

The application of the stereological methods in biological research has made a considerable progress. In so many fields the use of stereology has been undoubtedly successful. It was found that stereological methods reveal more differences between different wood species and between samples of the same wood. They may also explain many of the physical and
Technological properties of wood which are not well understood from conventional microscopy. This is due to the establishment of more basic and quantitative interrelationships between microstructural features and the properties and behavior of wood. The geometry of microstructure has turned out to be far more subtle than was generally realized (Zheng, 1976). There is so much known about structure-property relationships in metals but this knowledge is not well organized. Metallurgists are moving toward a full quantification of structure-property relationships in metal systems (Zheng, 1976). In spite of the progress made by the stereological approach in biological investigation, the application of stereology in biological research and materials of biological origin (like wood) still poses a number of problems (Wibel, 1976). The first of these problems is the nature and complexity of biological specimens which make it difficult to recognize all cell types. Secondly, stereological methods are derived on the basis of probabilistic models; the structural elements are supposed to be
randomly distributed, randomly oriented, and randomly intercepted by a stereological test procedure. Many cells and tissues also show a pronounced rotatory or anisotropy. Such anisotropic systems like wood, could be analyzed on a strict cross-section, perpendicular to the anisotropy axis, randomly cut and randomly intercepted by test lines. Alternatively one can use sections parallel to the anisotropy axis and orient a test line at a fixed angle.

Mechanical properties of wood

The term mechanical properties refers to the behavior of wood under applied forces. This behavior is modified in a number of ways, depending upon the kinds of forces exerted on the wood and the basic differences in the organization of wood that have already been noted. Forces expressed on the basis of unit area are known as stresses. There are three kinds of primary stresses that can act on a body. The force may be acting in compression if it shortens a dimension or reduces the volume of the body so that
is called a compressive stress, which is defined as the total compression force divided by the cross-sectional area of the piece being stressed. The force that tends to increase the dimension of volume is a tension force, and the stress exerted on the body is then a tensile stress. Shear stresses result from a combination of all these primary stresses; they cause fracture or bending in the body. The resistance of the body to the applied stress is known as the strength of the material. The strength of the material must be stated in terms of its compressive, tensile, or bending strength. The measure of the change in dimension resulting from applied stress is known as strain. This value is expressed in terms of the deformation per unit area. The calculation of stresses acting on short wooden columns are given below.

1. Calculation of the stress developed as a result of the action of force along the grain. Since a stress is force per unit area, the following equation holds:

\[ \sigma = \frac{P}{A} \]

where \( \sigma \) is the stress, \( P \) is the force or load, and

\( A \) is the cross-sectional area.
is the area upon which the force acts. If the force produces compression, the basic equation is:

$$\sigma_c = \frac{F_c}{A}$$  \hspace{1cm} (2)$$

where the subscript (c) indicates the stress acts in compression. If the force produces shear, the basic equation is:

$$\tau_s = \frac{F_s}{A}$$  \hspace{1cm} (1)$$

where the subscript (s) indicates the stress is acting in shear (Buckingham, 1962).

Methods of determining the strength properties of wood:

Two alternative methods for determining the strength properties of wood are available: service tests and laboratory experiments. Service tests are carried out under the conditions to which timber is exposed in use. In service tests the data take much longer time to collect and external factors likely to influence strength properties are more difficult to control and decentralization of the experiments increases their cost (Buckingham, 1962). Laboratory tests provide a practical
solution to all these problems. In the laboratory two classes of tests are made: tests on small clear specimens, and tests on timber in structural size. The tests of small clear specimens are of value for comparison of individual timbers. Since the tests are designed to avoid the influence of knots and other defects, the results do not indicate the actual loads that structural members can carry, and a reduction factor must be applied to obtain safe working stresses. Tests on timber of structural size allow for defects such as knots and splits. Their disadvantage is that large amounts of timber are required and it needs a long time to load large-sized test pieces to the point of failure.

The procedure for tests on small clear specimens of timber has been standardized. Tests of small clear specimens of many timbers have now been carried out. In spite of the limitations of the data obtained, the tests are of considerable practical importance.
for by consideration of the variability in proportions of different cell types, Sellegaard and Itzju (1962) related the physical characteristics of 20 softwood species to the differences of properties of wood in tension parallel to the grain and revealed that the single factor of greatest importance was specific gravity, which was related to both strength and modulus of elasticity. Luxford (1931) found that extractives increase the strength in compression parallel to the grain and bending strength. However, the presence of extractives influenced shock resistance in a negative manner (Malatesta, 1977).

Temperature is also an important factor which influences the strength of wood. It has been found that tensile strength across the grain and stiffness may be reduced to as little as a half and a third, respectively, in wet wood at temperatures below -20°C, (Tiemann, R. D., 1945). For dry wood there is a linear relation between temperature and crushing strength for a range of temperature from -70°C to +150°C, strength decreasing as temperature rises. The rate
of change increasing with the specific gravity. Above 160 0 strength decreases even more rapidly, owing to chemical decomposition.

> Sloping grain is an important factor influencing the strength of wood. Static bending and longitudinal tension are all markedly lowered with sloping grain. Thus at an angle to the grain of 15 the tensile strength, static bending and longitudinal compression are reduced to 45, 70 and 80 per cent of their respective strengths in straight-grained material (Desh, 1981). Ends also influence the strength of wood to a varying degree, depending on their size, position, and type. Other factors such as size and defects are also important strength reducing factors. The major types of defects which reduce the strength of wood are checks or splits, brittle heart and rot.

The important anatomical features influencing the strength of wood are cell length, the overlap between cells, the microfibrillar angle of the xylem layer, and the occurrence of compression wood and tension wood.
Materials:

The materials used in this study were specimens from eight different species of hardwood. The samples were collected from different geographical regions: *Gordia africana*, *Mukula* and *Meliicapilla* from Northern Province; *Dacryodes* from Eastern Province; *Honduras mahagoni*, *Honduras lanceolata*, *Honduras mahagoni*, and *Honduras chilenopita* from the Blue Nile Province; and *Honduras guianensis* from the Khartoum area. A short account of the economic importance and distribution of each of these hardwoods (as reported by Rohani, 1969) is given below:

*Gordia africana* (Chilili):

Widely distributed in Southern Darfur Province, on lower slopes of Jebel Marra up to 1500m. It is also found in Kordofan, Kassala, Bahr al Ghazal and Kanala Province. The wood is used for high-quality furniture, doors and windows, small boats and walking sticks. Also it is used for cabinet making, Joinery,

[...]

[Continued text]
found at Jebel Dair. It is also found in Southern Darfur and on the banks of the river Ummur. The wood is very suitable for furniture, construction, and also used for needles.

**Boscia images** (Torakaya)**

Widely distributed in Blue Nile (Rung area), Kordofan, Southern Darfur, and Southern Sudan. The wood is used locally in manufacturing match boxes, furniture linings, ply-wood, wooden kitchen ware, picture frames, and veneer. It is also used for the wood and charcoal and the tree produces frankincense gum.

**Eucalyptus camaldulensis** (Pan)**

It is an exotic tree introduced from Australia. It has a rapid rate of growth. It is suitable for a wide range of environmental conditions. It is raised mostly on the banks of the Blue Nile River and in irrigated plantations. The wood is used in transmission poles as well as for dimension lumber. It is used for fiber board, particle board, and pulp and paper industry. Also it is used for furniture and building construction.
Cinnebarra lanceolata (Dona):

It is native to Somalia and Saudi Arabia. It was first introduced into the Sudan in 1930. It was planted in Kassala on the banks of the River Gash. Irrigated plantations have been done at Khasheli, Girba and Khartoum green belt. The wood is light in colour and of medium density and considerable strength. It works well in most machines, but does not plane well due to distinct interlocked grain. It is used for general carpentry, building of boats and ship decking. It may produce good quality plywood.

Prosopis chilensis (Mesquite):

It is native to Peru and Bolivia, Central Chile and Northern Argentina. It is a very useful shade and fodder tree, well adapted to light soils, and probably nitrogen fixing. It is suitable for planting in subdesert regions. It is a very drought resistant and high yielder of biomass. The wood has rich dark brown heartwood, often with purplish hue. It is heavy with average density ranging from 0.9 to 0.9 g/cm³. It is coarse-textured, irregularly grained, hard, strong, and
very resistant to decay. It is easy to work, finishes smoothly, and takes a good polish. It is used locally for fuel. Pods are used as feed for cattle in dry regions, and can be ground into meal for concentrated rations.

Representative samples of each species were collected randomly from a large lumber supply.

For stereological counting 10mm x 10mm x 10mm blocks were cut randomly from different samples and five transverse microstone sections of 10 - 20 micrometers thickness were prepared from each species using a sliding microtome. These sections were stained and the chemicals used in their staining were safranine, fast green, 10% and 50% alcohol, clove oil, seder wood oil, xylene, distilled water, and Canada balsam. In addition to safranine, 10% hydrogen peroxide and glacial acetic acid were used for fiber preparation. These slides and covers were also used to prepare the sections for examination. Light microscope with a projector and a 15 point 100cm x 30cm square grid were also used.
Method:

For the quantitative characterization of the anatomical structure of wood, cross-sectional measurements were done and the fiber length for each species studied was determined using stereological methods.

1. Cross sectional measurement:

For cross-sectional measurements, transverse microtome sections of 10 - 20 micrometers thickness were randomly cut from small sectioning blocks taken randomly from each species. Five transverse sections were prepared and stained using fast green - safranin double-staining technique. The sections were then mounted on permanent glass slides for microscopic examination. Images of these transverse sections were projected through a microscope onto a 16-point 3mm x 3mm square grid as shown in figure 12. The test points were made by the intersections of two sets of four lines running perpendicular to each other making the square grid.
The total magnification of the image was chosen such that the diameter of the largest element (the vessels) was approximately equal to the grid spacing. Cellological counts were made on ten fields randomly selected from each slide. The microscope stage was rotated at angles chosen randomly using equal probability selection method. On each the parameters counted were: point fraction \( p_0 \) for vessels, fibers, longitudinal parenchyma, and rays. The point fraction was counted for cell wall and lumen of each cell type. The number of interceptions \( N \) of vessels, fibers, and longitudinal parenchyma per unit test line, and the number of each of the three cell types per unit area were counted. The rays were aligned parallel to one set of lines and perpendicular to the others. The point fraction \( p_0 \) was determined as shown in Figure 2. A grid is superimposed on the structure and the number of points lying in the plane of interest is counted. \( p_0 \) is the number of points counted divided by the total number of points in the grid. Figures 4-12 show photomicrographs of the cross-section in which all counts were made for the different species studied.
Figure 2.1

A 16 point square grid superimposed on a structure for the determination of point fraction or volume proportion for cell types $P_p$. 

$$P_p = \frac{5}{16}$$
The number of intersections per unit length of test line (T1) was determined as shown in Figure 3. Test lines of the grid were superimposed on the structure. The number of times these lines intersected cells outlines were divided by the total length of test line. The intersections of any line with two margins of a cell were counted as two points while tangents were counted as one point.

The total number of cells per unit test area was also determined as shown in Figure 4. The cells which were completely inside the grid area were counted as one complete cell. The cells which intersected the edge of the area of observation were counted as 1/2 cell, and those on the corners were counted as 1/4 cell. The total number of cells observed in the structure were then divided by the area of observation.
Figure 1
A 16-point square grid superimposed on a structure for the determination of the number of intersections per unit test line L.
A 16 point square grid superimposed on a structure for the determination of the number density of cell types or the number of features per unit test area.
For fiber length determination, chips were taken randomly from different specimens representing each species. These chips were macerated to isolate the fibers. They were macerated in 50/50 solution of 30 per cent hydrogen peroxide and glacial acetic acid. The cork was boiled in a water bath for 1 - 2 hours. The macerated fibers were stained with aqueous solution of safranine and deposited on permanent glass slides. Five slides were prepared to represent each species. These slides were projected through a projector onto a 16-point 30cm x 30cm square grid. Fifty fields were selected randomly from the slides to represent each species. Two stereological counts were measured, these were the number of point intersections with the test lines made by fiber boundaries per unit test length (Pn) and the number of fibers per unit test area (Nn). These were used to calculate the average fiber length for the different species studied.
Methods of computing some basic stereological parameters were used. These parameters were: fiber length, cell diameter, lumen diameter, double cell wall thickness, Shank's ratio, coefficient of cell rigidity, and fiber density index.

The fundamental relationship is:

\[ \bar{V}_P = \bar{V}_L = \bar{V}_A = \bar{V}_Y \]  

The average fiber length can be calculated from associated fibers as follows:

\[ \bar{L} = \frac{\sum L}{N} \]  

The average cell diameters may be obtained from \( \bar{L} \) and \( \bar{d} \) counts as given in the following equation (Staal, Iru, and Johnson, 1976):

\[ \text{Average cell diameter } d = \frac{\bar{N}_L}{\bar{N}_A} \]
Average lumen diameter (LD) may be calculated from point fraction (F_p) if the average number of cells per unit area (N_A) is measured. This equation can be expressed as follows:

$$\bar{D}_D = \sqrt{\frac{4F_p \text{ (lumen)}}{\pi N_A}} \quad (a)$$

This was derived as follows:

Average lumen area \( \bar{A} \) = \( \frac{F_A \text{ (lumen)}}{N_A} \)

Also \( \bar{A} = \frac{\pi d^2}{4} \) (assuming circular cross-section of cells)

\( \frac{\pi d^2}{4} = \frac{F_p \text{ (lumen)}}{N_A} \)
Symbols ratio \[ \frac{\bar{F}_L}{\bar{F}_A} = \frac{\sqrt{\frac{\bar{F}_L}{\bar{F}_A}}}{{\sqrt{\frac{\bar{F}_L}{\bar{F}_A} + \bar{F}_L}}} \]

Tsunaka ratio \[ \frac{\bar{F}_L}{\bar{F}_A} = \frac{\sqrt{\frac{\bar{F}_L}{\bar{F}_A} + \bar{F}_L}}{\sqrt{\frac{\bar{F}_L}{\bar{F}_A}}} \]

Another ratio which is the coefficient of cell rigidity may also be calculated from these dimensions:

Coefficient of rigidity \[ \frac{\bar{F}_L}{\bar{F}_A} = \frac{\sqrt{\bar{F}_L / \bar{F}_A}}{d} \]

Some ratios can be determined from point fractions:

E.g. :

Fiber density index \[ \frac{\bar{F}_D (\text{cell wall})}{\bar{F}_W (\text{lumen})} \]
**Mechanical properties**

The British standard method of testing small clear specimens of timber B.S.171:1957 was used for determining the density and mechanical properties of the eight Sudanese hardwoods.

Density test was carried out using the Poe standard. Blocks 2cm x 2cm x 2cm were used. Samples had been weighed then dried in an oven at a temperature of 103 ± 2°C (397 ± 4°F) until the weight was constant. The oven dry volume was then counted and the oven dry weight was divided by the oven dry volume to obtain the density of wood.

Compression strength parallel to the grain was tested according to the B.S.371:1957. The sample size was 30x30x80mm. The load was applied to the centre of the end at a rate of 0.01 mm/s. The universal testing machine used was the Lorenz-Hosemann. Maximum crushing strength was calculated by dividing the load to failure by the cross-sectional area.
For hardness the sample size was 20 x 20 x 60mm. The test requires determination of the load necessary to force into the test piece, to a depth of 0.65 cm, the hemispherical end of a steel bar or a steel ball, 11.3 mm in diameter. The rate of the penetration of the hardness tool was 0.01 mm/s. The test was carried out on both radial and tangential faces.

Shear test parallel to the grain was also done using casting 2, on side according to the B.S. 373:1957. The load was applied at a constant rate of crosshead movement of 0.01 mm/s. The direction of shearing was parallel to the longitudinal direction of the grain. The percent average shear stress (A.A.S.T.O.) was computed as follows:

\[
\text{A.A.S.T.O.} = \frac{V}{bh} \text{ Kg f./in}^2 \text{ (Radial or tangential)}
\]

where \(bh\) = area in shear in square in.

\(V\) = maximum load in Kg causing shear.
All test pieces were completely free from all types of defects including knots, end splits, warp, resin pockets, bark or cross grain. Each sample was machined with great care to the exact size required. Any samples showing defects were rejected from the test.
RESULTS AND DISCUSSION

The values obtained for the structural parameters were based on 2000 stereological counts made on the eight Suda-born hardwoods studied. Many structural parameters were obtained for each species as summarized in Tables 1 - 6. The average values for the strength properties are given in Table 7, and the correlation matrix is presented in Table 8.

The results obtained from this investigation can be classified into the following categories:

1. The quantitative anatomical structure of the eight species studied.
2. The mechanical properties.
3. The interrelationships between the structural properties and the mechanical properties.

1. The anatomical structure

The major cell types studied were vessel fibers, longitudinal parenchyma, and rays. Table 1 shows the average point fraction ($F_p$) or volume proportion.
<table>
<thead>
<tr>
<th>Angle</th>
<th>0°45'</th>
<th>0°90'</th>
<th>0°135'</th>
<th>0°180'</th>
<th>0°225'</th>
<th>0°270'</th>
<th>0°315'</th>
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<td>60°</td>
<td>90°</td>
<td>120°</td>
<td>150°</td>
<td>180°</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
for the different cell types for the species studied. The point function is an unbiased structural estimator of the average volume fraction ($V$) and area fraction ($A$).

$Q$. africana showed the highest volume proportion for vessels $n_1^V$ which had the value of 0.37. This indicates that it has the highest void volume which means that it should have low specific gravity. $E$. chilensis and $L$. arimori showed the lowest volume proportion for vessels (0.11) and (0.14) respectively. This means that they have also the lowest void volume at they were supposed to have the highest specific gravity. Then we compare the average number of vessels per unit area $n_V^V$ in $Q$. papilliferae and $Q$. africana, the former the larger number of vessels than the latter but with the smallest lumen diameter for vessels (0.07mm) while the latter has the biggest lumen diameter for vessels (0.23mm) as shown in Table 4. The average volume proportion for fibers $n_2^V$ was found to be highest in $Q$. africana (0.64) followed by
The total recoverable volume proportion for all coal material $P_{\text{ca}}$ is calculated by:

$$
P_{\text{ca}} = \frac{P_{\text{c}} + P_{\text{a}}}{100}
$$

where $P_{\text{c}}$ is the proportion of combustible material and $P_{\text{a}}$ is the proportion of ash material. The value of $P_{\text{c}}$ is determined by the method of analysis as described in the previous section. The proportion of ash material $P_{\text{a}}$ is determined by the method of analysis as described in the previous section.
<table>
<thead>
<tr>
<th>Species</th>
<th>Fiber length (mm)</th>
<th>Vessel diameter (μm)</th>
<th>Fiber diameter of LP (μm)</th>
<th>Fiber diameter of LP (μm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Pyrus</td>
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<td>0.073</td>
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<td>0.012</td>
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<tr>
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<td>0.158</td>
<td>0.012</td>
<td>0.016</td>
</tr>
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<td>Cannonia</td>
<td>0.959</td>
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<td>Sclerocarya</td>
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<td>0.179</td>
<td>0.015</td>
<td>0.026</td>
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<td>Apocynopsis</td>
<td>0.682</td>
<td>0.147</td>
<td>0.022</td>
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</tr>
</tbody>
</table>

LP = Longitudinal parenchyma
longifolia (0.008cm) for each of these. The diameter of longitudinal parenchyma was found to be longest in *S. hierococca* (0.036cm) followed by *S. africana* (0.033cm), and the smallest diameter was found in *S. canadulensis* (0.017cm) followed by *S. kosteri* (0.016cm). The longest fiber was found in *S. africana* (1.40mm) followed by *A. gayneri* (1.17mm), while the shortest fiber was that of *S. parviflora* (0.82mm) followed by *S. canadulensis* (0.71mm). The longest vessel diameter was that of *S. africana* (0.76mm) followed by *A. gayneri* (0.26mm).

Table 3 shows the average double cell wall thickness measured for the different species studied and for different types of longitudinal cells. The most important of all is the double cell wall thickness for fibers which was found to be largest in *S. canadulensis* (0.005mm) which has a high volume proportion for cell wall material and the lowest average volume proportion for cell lumen, while *A. parviflora* which has the highest volume...
<table>
<thead>
<tr>
<th>Species</th>
<th>Fiber (um)</th>
<th>Vessel (um)</th>
<th>Longitudinal parenchyma (um)</th>
</tr>
</thead>
<tbody>
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<td><em>Ixora</em></td>
<td>0.003</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td><em>Buea</em></td>
<td>0.005</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td><em>Euphorbia</em></td>
<td>0.003</td>
<td>0.004</td>
<td>0.002</td>
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<tr>
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<td><em>Sclerocarya</em></td>
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<td>0.003</td>
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<td><em>Cordia</em></td>
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<td><em>Boswellia</em></td>
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</table>
proportion for cell lumen and the lowest volume proportion for cell wall material, and also show the lowest value of double cell wall thickness (0.08 mm).

The important conventional ratios which have been used frequently in connection with quantitative wood anatomy were shown in Table 5. These ratios were given as averages. The ratios studied were Faber's ratio (FR) which is the ratio of double cell wall thickness to the lumen diameter. The ratio was found to be biggest for *E. guadalupensis* (1.6) followed by *E. lucifolium* (1.1) and the smallest for *E. brachyphloia* (0.5). The coefficient of cell rigidity (CR) is the ratio of the cell wall thickness to cell diameter. This ratio was found to be biggest for *E. guadalupensis* (0.29) followed by *E. kotschyi* (0.23) and smallest for *E. prostrata* (0.09) followed by *E.ylonii* (0.06). Fiber density index is the ratio of the average volume proportion for cell wall to the average volume proportion for lumen. This ratio was found to be biggest for *E. guadalupensis* (2.9) followed by *E. lucifolium* (2.7) and smallest for
<table>
<thead>
<tr>
<th>Species</th>
<th>Fibers (mm)</th>
<th>Vessels (mm)</th>
<th>Longitudinal parenchyma (mm)</th>
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<td>0.020</td>
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<tr>
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<tr>
<td>Species</td>
<td>Fiber Density</td>
<td>Vessel Ratio</td>
<td>Coef. of R, vessel</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------</td>
<td>--------------</td>
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<tr>
<td>Eucalyptus camaldulensis</td>
<td>2.00</td>
<td>0.018</td>
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<td>Clarnecarya trigon</td>
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<td>Cordia africana</td>
<td>1.19</td>
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<tr>
<td>Borneoella papuensis</td>
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<td>0.168</td>
<td>0.120</td>
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</tbody>
</table>

Coef. of R = coefficient of cell rigidity.
<table>
<thead>
<tr>
<th>Species</th>
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<th>$N_A(F)$</th>
<th>$N_A(LP)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus deglupta</td>
<td>8.91</td>
<td>4552.9</td>
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<tr>
<td>Philaloea</td>
<td>(2.31)</td>
<td>(1684.7)</td>
<td>(308.1)</td>
</tr>
<tr>
<td>Eucalyptus grandis</td>
<td>28.00</td>
<td>5250.9</td>
<td>512.0</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>(4.49)</td>
<td>(809.9)</td>
<td>(175.1)</td>
</tr>
<tr>
<td>Eucalyptus microcarpa</td>
<td>9.41</td>
<td>1919.7</td>
<td>59.0</td>
</tr>
<tr>
<td>Eucalyptus obliqua</td>
<td>(2.67)</td>
<td>(487.1)</td>
<td>(66.1)</td>
</tr>
<tr>
<td>Eucalyptus saligna</td>
<td>17.74</td>
<td>2060.2</td>
<td>227.7</td>
</tr>
<tr>
<td>Eucalyptus sideroxylon</td>
<td>(2.31)</td>
<td>(697.5)</td>
<td>(76.8)</td>
</tr>
<tr>
<td>Ficus</td>
<td>2.27</td>
<td>1017.1</td>
<td>331.6</td>
</tr>
<tr>
<td>Myrtaceae</td>
<td>(1.05)</td>
<td>(318.1)</td>
<td>(174.1)</td>
</tr>
<tr>
<td>Heterodaxa</td>
<td>9.93</td>
<td>1200.6</td>
<td>10.8</td>
</tr>
<tr>
<td>Acacia</td>
<td>(2.24)</td>
<td>(185.4)</td>
<td>(17.7)</td>
</tr>
<tr>
<td>Combretum africana</td>
<td>6.68</td>
<td>576.0</td>
<td>286.2</td>
</tr>
<tr>
<td>Eucalyptus caesia</td>
<td>(2.30)</td>
<td>(309.1)</td>
<td>(32.7)</td>
</tr>
<tr>
<td>Eucalyptus ptychocarpa</td>
<td>15.32</td>
<td>871.2</td>
<td>214.5</td>
</tr>
</tbody>
</table>

($V$) = Vessels  
($F$) = Fibers  
(LP) = Longitudinal parenchyma  
Numbers in parentheses are standard deviations.
The results showed that fiber density index was a good indicator for the specific gravity and strength properties of wood.

**III. Strength properties**

Table 7 shows the average values of the specific gravity based on oven dry weight and oven dry volume. The mechanical properties of the eight species were shown in the same table. The specific gravity ranged between 0.97 m³/g for *P. chilensis* and 0.77 m³/g for *B. pauperis*. The strength properties were determined at average moisture content ranging from 4 to 7% of dry wood. Average compression strength parallel to the grain was found to be highest for *P. caballus* (799.75 kg/cm²) and *B. hetschui* (731.75 kg/cm²), while *B. pauperis* showed the lowest compression strength parallel to the grain (317.61 kg/cm²). *P. caballus* and *B. hetschui* showed higher compression strength parallel to the grain than would be indicated by their specific gravities. This may be
### Table 7:

Average values of specific gravity and mechanical properties of eight Sudanese hardwoods.

<table>
<thead>
<tr>
<th>Species</th>
<th>Specific Gravity</th>
<th>Ultimate Compression Stress (Specimen 1)</th>
<th>Ultimate Compression Stress (Specimen 2)</th>
<th>Ultimate Tensile Strength (Specimen 1)</th>
<th>Ultimate Tensile Strength (Specimen 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prosopis</em></td>
<td>0.93</td>
<td>617.75</td>
<td>414.90</td>
<td>274.85</td>
<td></td>
</tr>
<tr>
<td><em>Gymnanthus</em></td>
<td>(0.04)*</td>
<td>(6.43)*</td>
<td>(78.09)*</td>
<td>(40.72)*</td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus</em></td>
<td>0.91</td>
<td>759.75</td>
<td>305.60</td>
<td>252.70</td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus</em></td>
<td>(0.04)</td>
<td>(5.83)</td>
<td>(51.04)</td>
<td>(34.43)</td>
<td></td>
</tr>
<tr>
<td><em>Pseudocedrela</em></td>
<td>0.80</td>
<td>521.75</td>
<td>310.50</td>
<td>209.13</td>
<td></td>
</tr>
<tr>
<td><em>Kotokoli</em></td>
<td>(0.03)</td>
<td>(3.95)</td>
<td>(17.31)</td>
<td>(33.63)</td>
<td></td>
</tr>
<tr>
<td><em>Conocarpe</em></td>
<td>0.76</td>
<td>588.50</td>
<td>315.00</td>
<td>200.00</td>
<td></td>
</tr>
<tr>
<td><em>Lincofolius</em></td>
<td>(0.03)</td>
<td>(3.96)</td>
<td>(20.85)</td>
<td>(10.91)</td>
<td></td>
</tr>
<tr>
<td><em>Albizzia</em></td>
<td>0.67</td>
<td>361.63</td>
<td>302.30</td>
<td>147.50</td>
<td></td>
</tr>
<tr>
<td><em>Avicenni</em></td>
<td>(0.03)</td>
<td>(22.71)</td>
<td>(29.73)</td>
<td>(10.91)</td>
<td></td>
</tr>
<tr>
<td><em>Sclerozarka</em></td>
<td>0.52</td>
<td>447.50</td>
<td>390.00</td>
<td>144.50</td>
<td></td>
</tr>
<tr>
<td><em>Kriyen</em></td>
<td>(0.03)</td>
<td>(30.42)</td>
<td>(18.91)</td>
<td>(4.15)</td>
<td></td>
</tr>
<tr>
<td><em>Cerqua</em></td>
<td>0.50</td>
<td>603.40</td>
<td>568.00</td>
<td>150.33</td>
<td></td>
</tr>
<tr>
<td><em>Africana</em></td>
<td>(0.03)</td>
<td>(31.96)</td>
<td>(6.91)</td>
<td>(15.70)</td>
<td></td>
</tr>
<tr>
<td><em>Aristolasma</em></td>
<td>0.33</td>
<td>377.63</td>
<td>332.50</td>
<td>122.32</td>
<td></td>
</tr>
<tr>
<td><em>Mangifera</em></td>
<td>(0.05)</td>
<td>(22.73)</td>
<td>(12.61)</td>
<td>(11.65)</td>
<td></td>
</tr>
</tbody>
</table>

* Specific Gravity (SG)
* Ultimate Compression Stress (Specimen 1)
* Ultimate Compression Stress (Specimen 2)
* Ultimate Tensile Strength (Specimen 1)
* Ultimate Tensile Strength (Specimen 2)

---

* Numbers in parenthesis are standard deviations.
due to the extractive materials that they contain we reported by Luxford (1931) who found that extractives influence the mechanical properties of wood and their greatest effect being to increase the strength in compression parallel to the grain. Hardness was found to be higher for E. chiliensis (914.60 Kg.f.) followed by E. schilleriana (730.50 Kg.f.). The lowest hardness was found to be that of E. apricus (238.50 Kg.f.) followed by G. africana (149.00 Kg.f.).

3- The interrelationships between the structural properties and the mechanical properties

Correlation analysis was carried out for the structural characteristics and the mechanical properties of the eight Guinean hardwoods. The correlation coefficient matrix (Table 9) showed that the average volume proportion for vessels $ar{V}(v)$ was highly and positively correlated with the average volume proportion for fibers $ar{V}(f)$ and the average volume proportion for cell wall
The average volume proportion for fibers was found to be negatively correlated with the average fiber length (-0.67). The average volume proportion for cell wall material was found to be highly and negatively correlated with the average fiber diameter (-0.79) and positively correlated with both coefficient of rigidity for fibers (0.71) and fiber density index (FDI) 0.79 and 0.77 respectively. The average fiber diameter was negatively correlated with the coefficient of cell rigidity for fibers and fiber density index (-0.72), (-0.79) respectively. All strength properties studied were found to be highly and positively correlated with the specific gravity. For compression strength parallel to the grain the correlation coefficient was 0.79, for hardness it was 0.74, and for shear strength it was 0.63. The specific gravity was also found to be highly and positively correlated with the average volume proportion for cell wall material (0.77), tankage ratio for fibers (0.51), and negatively correlated
with the fiber length \( \bar{\ell} \).

The structural parameters were reduced into four variables and that was done by taking one parameter to represent a set of highly correlated parameters. The four variables taken were the average volume proportion for vessels \( \bar{V}(V) \), average volume proportion for rays \( \bar{V}(R) \), average volume proportion for total cell wall material \( \bar{V}(CW) \), and average fiber length \( \bar{\ell} \).

Regression analysis was carried out using the four structural parameters as independent variables against specific gravity, compression parallel to the grain, hardness, and shear strength as dependent variables.

Multiple regression analysis revealed that the most important structural property that influences the specific gravity of the hardwood studied was the average volume proportion for total cell wall material which was the most significant of all
variables, average volume proportion for rays, and average fiber length as shown by the following three variable model:

$$S_g = -157 + 0.574 \bar{f}(R) + 1.89 \bar{f}(P_{aw}) + 0.233$$  \hspace{1em} (10)$$

where $S_g$ is the specific gravity, $\bar{f}(R)$ is the average volume proportion for total cell wall material, which was found to be highly significant, with partial $r^2$ of 0.295. This means that it is the most important structural parameter influencing the specific gravity of wood, $S_g$ is the coefficient of determination for the whole model. For this model, $R^2$ was 0.973. The average volume proportion for rays came second in its influence on specific gravity with partial $r^2$ of 0.285, while the other two independent variables had no significant effect on the specific gravity of wood compared with the former two variables as shown by the values of their respective $r^2$.

Among the species studied, *E. obliqua* and *E. caglaudana* showed the highest specific
gravities 0.31 and 0.11 g/cm³ respectively as shown in Table 7. Then we studied the anatomical structures of these two species and found that these species also has the highest volume proportion for cell wall material, so this explains why they have the highest specific gravities compared with B. napus which has the lowest average volume proportion for cell wall material and has the lowest specific gravity.

Compression strength parallel to the grain was found to be significantly influenced by the average volume proportion for cell wall material as the most important factor, followed by the average fiber length as shown by the following model:

\[ C_{\|} = 171.08 + 1214.03 \bar{V}(cv) + 141.9 \bar{L} \]  \hspace{1cm} (11)

where \( C_{\|} \) is compression strength parallel to the grain, \( \bar{L} \) is the average fiber length, and \( \bar{V}(cv) \) is the average volume proportion for cell wall material. \( r^2 \) for this model was 0.79, this indicates
that the significant differences between the
growth studied in compression strength parallel
to the grain is due to the variations in the
amount of cell wall material present in the wood
and average fiber length.

The regression analysis also showed that the
factors influencing hardness were found to be the
average volume proportion for cell wall material
which was the most significant structural
parameter, the average volume proportion for vessels
\( V(\nu) \), and the average fiber length \( L \) as shown in
the following model:

\[
E = -264.59 + 7.92V(\nu) - 2.30V(\nu) - 160.74L
\]

(1)

where \( E \) is hardness. The value of \( r^2 \) for the model
was 0.985.

Shear strength was not influenced by the
average volume proportion for vessels \( V(\nu) \) which
has a very weak correlation coefficient. The average...
volume proportion for rays has also shown no significant influence on shear strength. The most effective variables were found to be the average volume proportion for cell wall material and average fiber length as shown in the following three variable model:

$$S = -132 + 959.55F_{(5)} + 522.65F_{(6)} + 64.24D$$  

(13)

where $S$ is shear stress in kPa. This model has an $R^2$ of 0.902. Shear strength was found to be negatively correlated with the average fiber length, this was in contrast with the effect of fiber length in compression strength parallel to the grain.

The rest of the structural parameters were represented by three independent variables included the average volume proportion for fibers $F_{(5)}$, average fiber diameter $F_{(6)}$, and double cell wall thickness $D$. These variables were taken in a way that each variable represents two highly
correlated structural parameters and the important ratio which were: Fankela ratio for fibers RR, coefficient of cell rigidity CR for fibers, and fiber density index FD. Regression analysis was carried out to determine the interrelations between these three structural parameters and the mechanical properties of the different species studied. The regression analysis also showed that the most important structural parameters which influence the specific gravity of wood were the average fiber diameter and the average volume proportion for fibers as shown in the following model:

$$S_g = 1.13 + 0.39F(\bar{d}) - 41.11\bar{d}$$  \hspace{1cm} (14)$$

where $S_g$ is the specific gravity of wood and $\bar{d}$ is the average fiber diameter. This model has an $R^2$ of 0.911. The average fiber diameter had shown a small influence in compression strength parallel to the grain as shown by the following model:

$$\sigma = 751.72 - 1110.99\bar{d}$$  \hspace{1cm} (15)$$
where $\sigma / g$ is compression strength parallel to the grain, $d$ is the average fiber diameter, and $R^2$ for the model was 0.433 which indicates that the variation in compression strength was due to factors other than those three as mentioned before.

Hardness was found to be influenced by the average volume proportion for fibers and average fiber diameter as shown by the following model:

$$N = 7.31.04 \times 736.01^B^p (4) - 40051.92d$$  \hspace{1cm} (16)

where $H$ is hardness in Kg/f. This model has an $R^2$ of 0.819. This model showed that the important factor which influences the hardness of wood was the average fiber diameter which was highly and negatively correlated with the average volume proportion for cell wall material. The next structural parameter which influences the hardness of wood was found to be the average volume proportion for fibers, but its influence was smaller compared with the average fiber diameter.
This emphasizes the negative correlation between the average volume proportion for vessels and the average volume proportion for fibers. The same effect was found in shear strength as shown by the following model:

\[ S = 207.45 - 185.38 \rho(F) - 916.02 \rho(C) \]  

(17)

where \( S \) is shear strength parallel to the grain in kg/cm\(^2\). This model showed an \( R^2 \) value of 0.303.
CONCLUSIONS

The results of this study relate the structural characteristics of eight California hardwoods to their mechanical properties. From this study the following conclusions may be drawn:

1) Quantitative characterization of the anatomical structure of wood using principles of stereology has proved to be a useful tool for standardizing structure-property relationships.

2) Cell types, sizes, inclusions, and their distribution in different species of similar density were widely different suggesting that wood density alone is not a sufficient measure for wood properties, so wood anatomy is becoming very important for explaining variations in wood properties.

3) The use of stereological techniques has also proved to be a quick and accurate method which saves a lot of time and effort.
4) The strength properties of wood are influenced by cell properties individually and in combination.

5) Basic relationships could be established between mechanical properties and anatomical structure of various woods as obtained from the regression models.

6) The regression models obtained could be used for prediction of mechanical properties from anatomical structure.

7) The most significant structural parameters influencing the mechanical properties of wood were as follows:

The specific gravity of wood was found to be influenced by the average volume proportion for cell wall material, the average volume proportion for rays, the average volume proportion for fibers, the average fiber length, and the average fiber diameter.

Compression strength parallel to the grain was found to be significantly influenced by the
4) The strength properties of wood are influenced by cell properties individually and in combinations.

5) Basic relationships could be established between mechanical properties and anatomical structure of various woods as obtained from the regression models.

6) The regression models obtained could be used for prediction of mechanical properties from anatomical structure.

7) The most significant structural parameters influencing the mechanical properties of wood were as follows:

   The specific gravity of wood was found to be influenced by the average volume proportion for cell wall material, the average volume proportion for rays, the average volume proportion for fibers, the average fiber length, and the average fiber diameter.

   Compression strength parallel to the grain was found to be significantly influenced by the
average volume proportion for cell wall material, the average fiber length, and average fiber diameter in addition to other factors such as the amount of extraneous materials present in wood.

Hardness and shear strees were found to be significantly influenced by the average volume proportion for cell wall material, average volume proportion for vessels, average fiber length, and average fiber diameter.

The mechanical properties obtained for Eucalyptus occidentalis, Prosopis chilensis, and Pseudophragma heteroxylon indicate that they can best be used for structural purposes. Although Prosopis chilensis has high strength properties, its branching habit of growth is a limiting factor for using it as structural timber.

Conocarpus elongatus and Alaxia sylvestri are of moderate strength and can be used with Sclerocarya birrea, and Cordia africana (which have
relatively low strength) for furniture, joinery, and light construction.

*Roswellia papyrifera,* which has the lowest strength properties is not suitable for furniture but good for light industries such as match manufacture.
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Figure 5: A photomicrograph of the cross-section of *Eucalyptus occidentalis*. ×400
Figure 6: A photomicrograph of the cross-section of Conocarpus lanceolatus, X400
Figure 7: A photomicrograph of the cross-section of Albizzia gilmeri, X400
Figure 8: A photomicrograph of the cross-section of *Selaginella hiera.* X400
Figure 3: A photomicrograph of the cross-section of *Cardia africana*. x250
Figure 10: A photomicrograph of the cross-section of *H. papyrifera*. X400
Figure 11: A photomicrograph shows ascocarpet fibers of *Fomes annosus*. X400.
Figure 12: A 16-point square grid on a transverse wood section. X400
لا تسمى "الحروف العربية"
وقد من هذه الدراسة أن أهم العوامل الفرعية التي تؤثر على الشؤون الصحية في المنطقة العربية. هذه العوامل تشمل نمط الحياة، والبيئة، والتعليم، والرعاية الصحية، والاختيارات الشخصية.

وقد أظهرت الدراسة أن هناك تأثرًا ملحوظًا بين بعض العوامل الصحية والبيئية. حيث أن العوامل البيئية مثل التلوث và التعرض للوقود والطاقة البدنية، تؤثر بشكل مباشر على الصحة العامة. وتشير بعض الدراسات إلى أن العوامل الاجتماعية مثل الفقر والتعليم، لها تأثير مباشر على الصحة العامة.

بالإضافة إلى ذلك، فإن العوامل الثقافية، الاجتماعية، والاقتصادية، تؤثر بشكل كبير على الصحة العامة. حيث أن العادات والتقاليد، وتكوين الأفكار، وطريقة العيش، تؤثر بشكل كبير على الصحة العامة.

إلى حد ما، فإن العوامل الفرعية، والبيئية، الاجتماعية، والاقتصادية، والثقافية، تؤثر بشكل مباشر على الصحة العامة. فكل من هذه العوامل، يمكن أن يكون لها تأثيرًا كبيرًا على الصحة العامة.