Part II—ELASTIC AND THERMAL PROPERTIES OF TIMBER—

Part II

ELASTIC AND THERMAL PROPERTIES OF TIMBER

I Chapter—INTRODUCTORY

1 Early History of the Study on Timber

A On Mechanical and Structural Properties

Among naturally occurring substances which can almost from the native state, be applied for practical constructional purposes, wood takes a prominent place It is, therefore, not surprising that from very early times, timber has been employed for building houses and boats and for making weapons of offence and defence With the advent of civilization new and wider fields of application have been opened up for this commodity It is, however, strange that until quite recently, all the technical and practical knowledge on this material has been the monopoly of carpenters and artisans and, as such, has remained quite empirical The increased application of wood for structural purposes especially of bridges, fast moving railway carriages and æroplane fuselage has resulted in the accumulation of a large amount of useful but uncoordinated information on the bulk properties of wood while the application to musical instruments and objects of artistic carving has extended our knowledge of its properties in small pieces A systematic scientific study of wood is of fairly recent origin and even after such a study had been started, the practical builder, with perhaps a certain amount of justification, looked askance at the scientific conclusions The real difficulty in the scientific investigation of wood lies in the fact that there are innumerable varieties of timber and the variations within the same species are again innumerable Further, being a biological product, subject to great variations in structure and characteristics due to variations in conditions of growth, it is difficult to expect any uniformity of values even in specimens of the same species It is, therefore, not surprising to find that the values obtained by laborious investigations, however good they might have been with respect to the specimens studied, could not be relied upon to apply to other cases Apparently difficulties and probably disappointments encountered by practical builders on account of these causes have been debited to the scientific achievement and led to the discrediting of scientific information on the subject[1]

The proper approach to a solution of this difficulty would appear to lie in studying the physical properties of wood in relation to some easily determinable basic character of the material, like, for instance its micro-structure, so that when any particular piece of timber is to be applied for a specific purpose, it will be only necessary to determine this latter basic character and to deduce therefrom other physical properties The micro-anatomical character of wood will be the best basic factor to take, since it is known that even small variations in conditions of growth register themselves permanently by changes in the micro-structure Besides the practical utility such a systematic study would have a large fundamental interest in that it will help to elucidate the properties of a highly complex biological product like wood on the basis of simple fundamental physical and chemical laws

Almost all the investigations on timber carried out in the last century and the first two decades of this century have been the work of certain timber testing laboratories and forest departments, in which the ultimate strength at breaking load has been studied The results of such investigations had to be used by the practical builder with a large and quite variable factor of safety depending upon the nature of the work In most of the early work no attempt has been made to find out the modulus of elasticity of the material and in later work where the modulus is given it is more in the nature of a casual information incidentally obtained in the course of the investigation rather than the result of a careful and systematic study of that property[2] It was only after the chemical nature of the wood substance and the physical structure of timber had been studied that a fundamental interest in the elastic properties of the material was aroused The importance of elastic moduli, particularly of Young's modulus, in the investigation of the fundamental structure and constitution of complex substances was gradually being recognised and stressed[3] Staudinger's investigations on the constitution of polymers of high molecular weight paved the way for an explanation of mechanical properties of natural and synthetic substances in relation to constitution The simultaneous X-ray investigations of complex organic substances supplied the necessary additional information for the calculation of mechanical properties from the structural standpoint

The *first attempt to correlate the physical properties* of wood to its micro-constitution was made by Nageli[4] who studied the optical double refraction and swelling of wood in relation to its structure as revealed under the microscope On the basis of his studies, he proposed the micellar theory of wood structure, according to which, the cellwall of wood fibres is built of micelles or groups of crystallites arranged in spiral form He also arrived at certain specific conclusions regarding the relation between the directions of maximum and minimum optical anisotropy and swelling on the one hand and micellar orientation on the other Several workers have followed up Nageli's lead but most of what has been subsequently done has been physiological or morphological and not physical Though some of Nageli's conclusions have been subsequently shown to be erroneous, the micellar conception of ultimate structure has been accepted in general Pfeffer[5] in his 'Pflanzen-physiologie' accepts the micellar structure as the ultimate units of which organised bodies are formed just as molecules and atoms are the ultimate units of chemical structure He, however, thinks that not all physical properties are traceable to micellar structure Thus, for example, he says that properties like anisotropic swelling and double refraction might be due to the axes of the micelles being of different lengths in different directions or of micelles being bound to one another with different forces in different directions while he maintains that the great differences in rigidity and elasticity of different cell-walls are mainly the result of their specific molecular structure Robinson[6] studying the permanent deformation of timber after failure under mechanical strains, thinks that the mechanical properties of timber depend more upon the nature of the cell-wall substance than upon the arrangements of its parts He considers the cell-wall to be essentially a colloid and thinks that all the mechanical properties of wood can be deduced by treating wood as a colloidal gel He considers wood to be a superviscous fluid whose viscosity in the course of growth has attained a value corresponding to that of a rigid gel The formation and growth of such a gel are, according to Robinson, in conformity with the principles of surface adsorption and surface energy at the surface of the proto-plasm where first pectic substances and then cellulose go on accumulating and increasing the viscocity of the proto-plasm till the whole substance settles down into a rigid gel He considers growth to take place not only by the addition of fresh cells but also by the stretching of existing cells, the anistropy of the cell-wall being due to the permanent deformation caused by the stretching during growth The striations in cell-walls first observed by Mohl[7] and correlated by Nageli with axes of micellar orientation are considered by Robinson to be the planes of slipping in the cell-wall substance produced by the mechanical tension during growth

Thus for the first time since Nageli proposed his crystallite micellar theory of cell-wall structure in 1860, was a view put forward in 1920 which suggested the micellar conception to be unnecessary and inconsistent with the accepted views on the structure and properties of colloidal gels Robinson's opposition was however short lived, for within the next few years Nageli's ideas were verified on almost what one might consider direct visual evidence Almost simultaneously with Robinson's work was started a vigorous investigation of wood structure by X-ray methods Shortly after Debye and Shearer developed their technique of X-ray study of pulverised material, Ambronn[8] suggested a search for the crystallites in wood by the X-ray method and his suggestion has been followed up by a large number of workers in the field Among the more important investigations on wood should be mentioned those of Herzog[9], Jancke[10], Polanyi[11], Ritter[12], Mark[13], Meyer[14], Clark[15] and Astbury[16] These investigators have obtained more or less consistent results regarding the existence and size of crystallites, the micelles composed of these crystallites and the manner of arrangement of these micelles[17] The best and perhaps the most direct evidence of the miceller conception is that provided by the ultra-microscope with the Spierer lens Seifriz[18] in collaboration with Spierer has examined cellulose with this arrangement and Thiessen[19] has extended this investigation to wood both in the sound state and in various stages of decay down to the condition of coal By this method structural details of the cell-wall have been photographed which are in conformity with the micellar theory of the structure of cellulose in wood More recently cellulose films have been examined by electron diffraction methods by Netta and Baccaredda[20] and the results confirm the previous X-ray investigations A study of the magnetic anisotropy of wood has enabled Nilakantan[21] to establish the crystalline character of cellulose in wood Chattaway and others[22] have studied the micro-anatomical characteristics of wood with a view to correlate them with the natural order and classification of different species

Carrington[23] has made a detailed study of the elastic moduli of English and spruce has measured, in definitely shaped specimens, the values of the Young's modulus, Poisson's ratio and rigidity modulus Treating wood as an anisotropic body with three mutually perpendicular planes of symmetry i e , like a crystal belonging to the rhombic variety, he has evaluated from his experimental results the nine elastic constants characteristic of rhombic structure Horig[24] has utilised Carrington's results for a detailed investigation of the elasticity of wood from the view point of Voigt's theory of elasticity of anisotropic bodies and has also drawn the elastic surfaces both for extension and torsion Following up a suggestion of Horig, Schluter[25] has measured the elastic constants of a few types of German timbers corresponding to the English spruce, such varieties being the ones most commonly used in the construction of the resonance chambers of musical instruments

B On Thermal Properties

The amount of study on the thermal properties of wood has been much smaller than that on its mechanical properties. Further there has been frequent contradiction of the results of one observer by the investigations of another Thus one observer maintained that wood possessed a negative coefficient of thermal expansion while another gave for wood quite a large positive coefficient In the early investigations on the thermal properties of wood, the role of moisture in wood has not been properly considered, with the result that varying conclusions were obtained by different observers since the specimens studied had evidently contained varying quantities of moisture

The fact that wood is a poor conductor of heat has been known from very early times and the provision of wooden handles for spits and soldering irons is a very ancient custom The use of wooden planks under the ceiling of particularly tiled structures to keep off the rigours of both sun and frost as well as the covering of the floor and walls in cold countries with wood panels is an important application of this property of wood However, both on account of the cost of the material and the risk of fire attending upon its use, the practice is limited in its scope An additional impetus to the large-scale application of this property of wood started with the development of the cold storage industry and refrigerator ships intended for the transport of cold-stored food-stuff had to be provided with some good non-conducting materials Indeed as much as fifteen to twenty per cent of the total tonnage of a refrigerator ship[26] consist of thermal insulating material and this works out at the rate of about 30 lbs of insulating material for every cubic foot of available cold storage space A systematic study of the thermal properties of wood and related insulating materials with a view to diminish the quantity of material per unit volume of storage space and also to employ it in the most efficient manner will therefore be of great practical importance

The earliest work on the thermal conductivity of wood was that of Forbes[27] who studied this property in the transverse and longitudinal directions The low value of the conductivity made the experimental determination a matter of difficulty till the disc arrangement of Lees and Chorlton[28] and of Lees was introduced By employing his method Lees[29] has measured the thermal conductivities of a large number of poor conductors including wood. Eucken[30], using an apparatus designed by himself made a wide study of different non-metallic substances, crystalline, amorphous and mixed and came to the conclusion that crystalline substances showed a diminution of conductivity with increasing temperature while the reverse was the case with amorphous substances. Eucken was the first to attempt a correlation between conductivity and other physical characteristics like molecular weight, number of atoms in the molecule, melting point etc. Barratt[31] employing an apparatus designed by himself determined the thermal conductivity of several non-metallic substances including wood and concluded that for non-metals the general thermal conductivity increased with temperature and that the conductivity of most woods increased rapidly with temperature. Barratt and Winter[32] determined the thermal conductivity of wood in very small pieces and have formulated a theory of heat conduction for such cases. Herman[33] working with a number of American woods found that thermal conductivity diminishes with density. The American Forest Department has measured the thermal conductivity of a number of American timbers. In all the available literature, however, there is hardly any information regarding the variation of conductivity of wood with respect to direction and even where some information is available, as in the work of Forbes, there is no indication as to whether the longitudinal conduction refers to the radial or the tangential plane.

Coming next to the thermal expansion of wood, one finds that perhaps this is the property that has received the least attention at the hands of both scientists and engineers and yet wood possesses a thermal expansion along its fibre of more than half the value of mild steel and across its fibre a value nearly ten times that of steel. The practical builder and the structural engineer have got to make detailed calculations of the effects of thermal expansion of iron in all practical structures and machines and provide proper allowances or arrangements against trouble on account of expansion with heat. Still there is next to no allowance made for such effects in the case of wooden structures The chief reason for this from the engineer's point of view is the fact that a large value of thermal expansion by itself is not of any serious consequence to a structure unless it is associated with a large elastic modulus and a good thermal conductivity Wood is far inferior to iron in these two properties, so that even after hours of exposure to the hot sun in the course of a day, only the surface layers of wood change temperature appreciably and on account of the low value of the Young's modulus of wood, the mechanical stress called into play by the surface change of length is well covered by the usual factor of safety in structures In a transverse direction the very much greater expansion might introduce an appreciable stress but for the fact that in all woods, the transverse elasticity is very much smaller than the longitudinal one so that the stress still remains quite small

The first attempt to measure the thermal expansion of wood was made by Struve[24] who studied the expansion of oak along the longitudinal direction Villari[35] next studied the thermal expansion of a large number of European timbers both along and across the fibres He was the first to call attention to the very large anisotropy of expansion, a value as high as 25 1 in some of his specimens Glatzel[36] using an apparatus designed by himself measured the thermal expansion of several woods along the fibre direction and mentions that the values obtained by him for the expansion across the fibre direction for only two specimens came out to be very much larger than the longitudinal values He, however, thought that it might have been caused by the uncertain amount of moisture in his specimens and was therefore inclined to leave it as an open question Indeed he has not even given these cross-expansion values in his paper The most recent work on this subject would appear to be that done in the Forest Products Laboratory of America and quoted in text-books[37] on wood

The author is not aware so far of any work correlating structure with the elastic or thermal properties of wood It was, therefore, considered worth while to undertake a systematic study of these properties, following up the line of work previously done by the author[38] on the elastic properties of another naturally occurring substance viz., mother-of-pearl

2 Scope and Materials of Present Study

In the present investigation an attempt has been made to study the elastic properties, thermal expansion and thermal conductivity of wood in relation to its structure Indian timbers were chosen for the study not only on account of their easy availability but also because they have not been studied so far in investigations of this kind Three varieties of timber of high density, two of medium density and one of low density were chosen from among the most commonly employed Indian timbers The materials were supplied to the author specially for this work by the courtesy of the Forest Department of the Government of Travancore The specimens were not subjected to any special seasoning process The trees after being cut were allowed to lie in the forests for about ten months From near the top ends of these trees but not close to the branching positions, transverse, radial and tangential sections were cut out and these sections, each about two inches in thickness, were left exposed to bright sunshine during the whole of March in Madras. The sections examined were all mature specimens of their kind having developed a large proportion of heartwood except in the case of the lightest specimen which by nature forms no heartwood at all The transverse sections were taken out of full discs cut out of the tree normal to the length of the trunk while for radial and tangential sections, planks sawed in the appropriate directions of the same trunk were used The lines of growth i e, the fibre directions and the annual rings were all very clearly visible specially after just smoothing up the surface by a few rapid strokes of the plane The test-pieces were all marked out on the various sections in definite directions with respect to the fibre directions, then cut off with a thin saw and finally polished and finished to exact dimensions by being rubbed on increasingly fine grades of sand-paper

In the case of the transverse section the following procedure was adopted Although theoretically a tree is assumed to grow by uniformly building round the pith or the axis in successive growing seasons in regular annual rings it is in practice found that the growth round the axis is not symmetrical all round This was the case not only in the specimens studied but seems to be the general case with the symmetrical growth as an occurrence of great rarity Out of more than a hundred trunks of different kinds of timber found in a depot only one instance of an approximately symmetrical growth round the axis was found In general, the trunks are more or less cylindrical but the pith does not coincide with the axis of the cylinder A diameter of the section passing through the pith is divided into two unequal segments by the position of the pith It has been found that this diameter will serve as an axis of elastic symmetry for the section Thus, P, in fig 11, p 259 is the position of the pith and the diameter APB of the section is an axis of symmetry The shorter segment PA of the axis of symmetry is chosen as the reference direction and test-pieces are cut out at definite inclinations to PA The test-pieces thus cut out were employed for the measurement of elasticity and thermal expansion For measuring the thermal conductivity, discs of about 10 cm diameter and three to four mm thickness were prepared separately from the different sections

A brief description of the different kinds of timber studied is given below The scientific name is given first followed by the natural order in brackets The local Indian names are given in square brackets and the English name where known is given immediately afterwards

I—'Terminalia Tomentosa' (Combretaceæ)

[Thembavu–Malayalam , Karumaruttu–Tamil] Indian Laurel

This tree grows throughout India in deciduous forests from the sea-level up to about 2000 ft upwards The timber is used extensively for making country carts, furniture and house-building The bark is used in dyeing and tanning

II—'Terminalia Paniculata' (Combretaceæ)

[Maruthy–Malayalam, Ven Maruthy–Tamil]

This tree also grows in deciduous forests from 0 to 2000 feet above sea-level and is used extensively as a substitute for the more costly teak The timber yields good planks for building purposes

III—'Artocarpus Hirsula' (Urticacæ)

[Anjili–Malayalam, Anjili or Ayani–Tamil] Jungle Jack

This is a large tree growing wild in forests and also grown extensively in private compounds The wood is easy to work, fairly light and has got a beautiful golden colour which, unlike teak, does not become dark with age Besides extensive application for building purposes and furniture, the wood is employed for making match boxes and splints

IV—'Dalbergia Latifolia' (Leguminosæ)

[Etti–Malayalam, Thothagatti–Tamil] Bombay Rosewood

This is a large tree growing on plains and hills up to an altitude of 4000 feet above sea-level The timber is hard and heavy, dark-brown or black in colour and takes a high degree of polish It is valued very much for all kinds of ornamental carving, furniture, gun-carriages, tool-handles etc

V—' Tectona Grandis ' (Verbenacæ)

[Thekku—Malayalam, Tamil] Teak

This is a tree well-known even outside India for its great usefulness and natural immunity against attack by termites It grows to very large sizes in deciduous forests up to an altitude of 3500 feet and the timber is used for almost all purposes for which wood can be employed

VI–' Bombax Malabaricum '–(Malvæcæ)

[Elavu–Malayalam, Ilavu–Tamil] Cotton tree

This tree grows both in deciduous and evergreen forests and yields a timber which is very soft and light and easily attacked by termites and boring beetles On account of its extreme lightness ftness, the wood is good for making matches and toys and trunks tied together serve as good fishing boats The tree , its English name from the fact that it bears a fruit which on yields cotton This cotton though unfit for spinning or weaving isively used for quilts, pillows and hospital dressings

HAPTER—EXPERIMENTAL METHODS AND RESULTS

I ELASTIC PROPERTIES OF TIMBER

The present investigation has been confined to the measure- f the Young's modulus of wood of different varieties in dif- lirections with respect to the lines of growth in timber The of obtaining the test-pieces has already been described in 2 of Chapter I

A Preliminary Experiment—It is a common engineering ion that the values of mechanical strength deduced from ex- nts on small specimens are no proper guide for large scale g purposes and that tests, in order to be really useful, should lucted upon specimens of actual sizes employed in the con- n Each annual addition of wood to a tree is in the nature of w cylindrical tube of wood-substance, shrunk on to the pre- existing tree, more after the design of heavy cannon This yer of fresh material in the course of growth, hardens and he inner portion firmly Such a structure helps to produce e uniform stress-distribution throughout the material and y improve the mechanical efficiency of the structure[39] It etore, reasonable that cutting through such a structure to a small test-piece is liable to interfere with mechanical h considerably But Young's modulus is on quite a different , in that it is a property related more to molecular structure microscopic or macro-molecular structure Hence it is quite y that Young's modulus will depend upon the size of the speci- iosen, so long as the size is large compared to micellar dimen-

To clarify this point and obtain experimental justification, if e, for this contention, a teak-wood joist (8 ft × 6 in × 3 in) was chosen and its Young's modulus was determined by a di bending test Afterwards out of this joist, four smaller pieces (e 100 × 2 × 2 cm) were cut out from different portions and the ela modulus of these four test-pieces was found out again by a bend test From each one of these four pieces, again, two smaller pie (20 × 1 × 1 cm) were prepared and the Young's modulus of each these eight pieces was again measured by a similar method T results are given in the following Table I It will be noticed t the values of the Young's modulus do not show any systematic var tion with size and that the variations are within the limits of expe mental errors

TABLE I

Young's Modulus and Size

	Large Size 250 × 15 × 7 cm	Medium Size 100 × 2 × 2 cm	Small Size 20 × 1 × 1 cm
Young's Modulus in Dynes per sq cm			$1\ 64 \times 10^{11}$
			$1\ 60 \times 10^{11}$
		$1\ 58 \times 10^{11}$	
			$1\ 60 \times 10^{11}$
		$1\ 61 \times 10^{11}$	
			$1\ 59 \times 10^{11}$
	$1\ 62 \times 10^{11}$	$1\ 61 \times 10^{11}$	
			$1\ 62 \times 10^{11}$
		$1\ 63 \times 10^{11}$	
			$1\ 67 \times 10^{11}$
			$1\ 57 \times 10^{11}$
			$1\ 66 \times 10^{11}$
Mean	$1\ 62 \times 10^{11}$	$1\ 61 \times 10^{11}$	$1\ 62 \times 10^{11}$

Having settled the preliminary point, the main experiment was carried out on the six different kinds of timber already chosen. To begin with, out of each variety of timber, pieces were cut out of the main block in the proper directions with dimensions nearly twice those required for the finished test-piece and these pieces were left inside an air-oven electrically maintained at 102°C for a period of not less than 48 hours. A shallow basin of concentrated sulphuric acid was also kept inside the oven. The specimens thus dried were left in the open cupboard in the laboratory for a week so that they reached what is called an air-dry condition by absorbing a certain amount of moisture from the atmosphere. The air-dry condition gives a more stable mechanical state than the oven-dry condition and is further nearer to the conditions obtaining in the actual application of wood. Further, experiments, conducted on such air dry specimens gave consistent results even when measurements were made with intervals of two or three weeks in between, while the values obtained with fresh oven-dry specimens were fluctuating with time in the course of the day. The air-dry specimens thus prepared were afterwards worked to exact dimensions required for the test by planing and sand-paper polishing and the value of Young's modulus was determined by Koenig's method of double optical lever with load at the centre. The average size of test-pieces was about 20 × 1 × 1 cm.

After measuring the elastic modulus, the over-all dimensions of the pieces were measured and their masses also were determined. Thereby the density of the various test-pieces was determined.

The tables 2 to 13 give the values of the Young's modulus and density for the various specimens studied.

The figures I to VI represent the curves showing the variation of Young's modulus with direction in the three principal sections of the different timbers. Polar co-ordinates have been chosen for the representation with the X-axis as the reference axis. The length of the radius vector in any direction gives the value of the modulus in that direction.

TABLE II

Value in the transverse direction

Direction	Density gms/cm^3	Young's Modulu in dynes/cm^2
0	0·99	$0·215 \times 10^{11}$
30°	0·98	$0·197 \times 10^{11}$
60		$0·196 \times 10^{11}$
90°	0·97	$0·195 \times 10^{11}$
120°	0·95	$0·148 \times 10^{11}$
150°	0·99	$0·256 \times 10^{11}$
180°	0·97	$0·095 \times 10^{11}$

TABLE III

Value in the longitudinal direction

Direction	I–Radial		II–Tangential	
	Density	Modulus	Density	Modulus
0	1·03	$0·917 \times 10^{11}$	1·09	$1·214 \times 10^{11}$
30°	0·98	$0·323 \times 10^{11}$	0·93	$0·333 \times 10^{11}$
60°	0·996	$0·36 \times 10^{11}$	0·97	$0·186 \times 10^{11}$
90°	0·99	$0·135 \times 10^{11}$	1·00	$0·123 \times 10^{11}$

TABLE IV

Value in the transverse direction

Direction	Density gms/cm³	Young's Modulus in dynes/cm²
0	0.99	0.289×10^{11}
30	0.99	0.281×10^{11}
60	0.98	0.277×10^{11}
90	0.98	0.274×10^{11}
120	0.97	0.246×10^{11}
150	0.98	0.253×10^{11}
180	0.99	0.230×10^{11}

TABLE V

Value in the longitudinal direction

Direction	I–Radial		II–Tangential	
	Density	Modulus	Density	Modulus
0	1.09	1.39×10^{11}	1.08	1.17×10^{11}
30	...	0.327×10^{11}	...	0.365×10^{11}
60	...	0.245×10^{11}	...	0.316×10^{11}
90	0.908	0.191×10^{11}	0.99	0.254×10^{11}

Young's Modulus of 'Artocarpus Hirsuta'

Table VI

Value in the transverse direction

Direction	Density in gms/cm³	Young's Modulus in dynes/cm²
0°	0 66	$0\ 183 \times 10^{11}$
30°	0 62	$0\ 172 \times 10^{11}$
60°	0 61	$0\ 174 \times 10^{11}$
90°	0 67	$0\ 158 \times 10^{11}$
120°	0 69	$0\ 172 \times 10^{11}$
150°	. .	$0\ 177 \times 10^{11}$
180°	0 61	$0\ 135 \times 10^{11}$

Table VII

Value in the longitudinal direction

Direction	I–Radial		II–Tangential	
	Density	Modulus	Density	Modulus
0°	0 61	$0\ 967 \times 10^{11}$	0 651	$1\ 098 \times 10^{11}$
30°	.	$0\ 290 \times 10^{11}$	. .	$0\ 346 \times 10^{11}$
60°	...	$0\ 123 \times 10^{11}$	0 62	$0\ 165 \times 10^{11}$
90°	0 57	$0\ 093 \times 10^{11}$	0 57	$0\ 113 \times 10^{11}$

Young's Modulus of 'Dalbergia Latifolia'

Table VIII

Value in the transverse direction

Direction	Density gms/cm^3	Young's Modulus in dynes/cm^2
0°	0 94	0 251 × 10^{11}
30°	...	0 227 × 10^{11}
60°	.	0 222 × 10^{11}
90°	0 92	0 221 × 10^{11}
120°	0 88	0 132 × 10^{11}
150°	..	0 166 × 10^{11}
180°	0 90	0 206 × 10^{11}

Table IX

Value in the longitudinal direction

Direction	I–Radial		II–Tangential	
	Density	Modulus	Density	Modulus
0°	0 90	1 483 × 10^{11}	0 92	1 733 × 10^{11}
30°	..	0 670 × 10^{11}	..	0 558 × 10^{11}
60°	..	0 387 × 10^{11}	...	0 398 × 10^{11}
90°	0 88	0·194 × 10^{11}	0 89	0 231 × 10^{11}

Young's Modulus of 'Tectona Grandis'

Table X

Value in the transverse direction

Direction	Density gms /cm ^{3}	Young's Mo dynes/cn
0	0 84	0 204 × 1
30°	...	0 181 × 1
60°	...	0 184 × 1
90°	0 81	0 186 × 1
120°	..	0 189 × 1
150°	0 78	0 176 × 1
180°	0 77	0 121 × 1

Table XI

Value in the longitudinal direction

Direction	I–Radial		II–Tangentia	
	Density	Modulus	Density	Modu
0	0 85	1·98 $\times 10^{11}$	0 80	1 550 ×
30°	..	0 331 $\times 10^{11}$	...	0 497 ×
60°	...	0 193 $\times 10^{11}$	...	0 266 ×
90°	0 79	0 095 $\times 10^{11}$	0 73	0 144 ×

TABLE XII

Value in the transverse direction

Direction	Density gms./cm³	Young's Modulus in dynes/cm.²
0°	0 41	$0\ 0800 \times 10^{11}$
30°	0 39	0.077×10^{11}
60°	0 37	$0\ 068 \times 10^{11}$
90°	0 38	$0\ 0699 \times 10^{11}$
120°	0 39	$0\ 0722 \times 10^{11}$
150°	0 38	$0\ 0684 \times 10^{11}$
180°	0 32	$0\ 0592 \times 10^{11}$

TABLE XIII

Value in the longitudinal direction

Direction	I–Radial		II–Tangential	
	Density	Modulus	Density	Modulus
0°	0 65	$1\ 138 \times 10^{11}$	0 56	$1\ 045 \times 10^{11}$
30°	0 54	$0\ 227 \times 10^{11}$	0 52	$0\ 242 \times 10^{11}$
60°	0 49	$0\ 104 \times 10^{11}$	0 50	$0\ 0637 \times 10^{11}$
90°	0 48	$0\ 0594 \times 10^{11}$	0 48	$0\ 0569 \times 10^{11}$

ELASTIC PROPERTIES OF WOOD

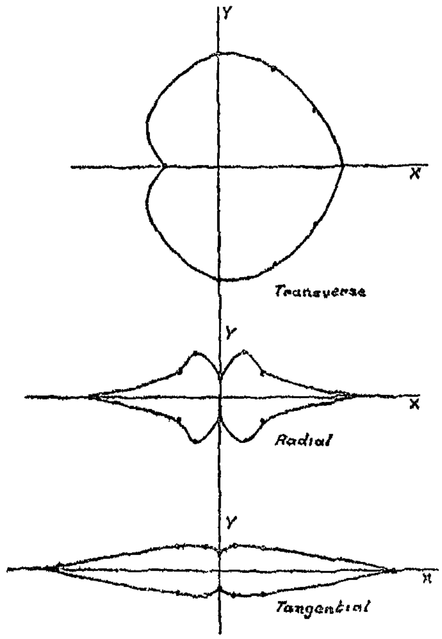


Fig No 1
Young's Modulus of Terminalia Tomentosa

ELASTIC PROPERTIES OF WOOD

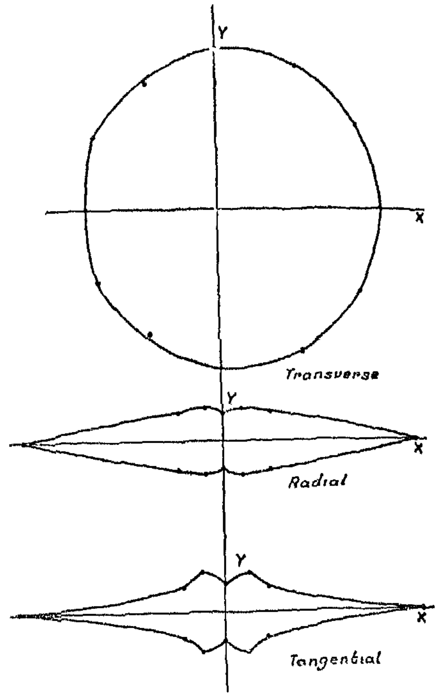


Fig No 2
Young's Modulus of Terminalia Paniculata

ELASTIC PROPERTIES OF WOOD

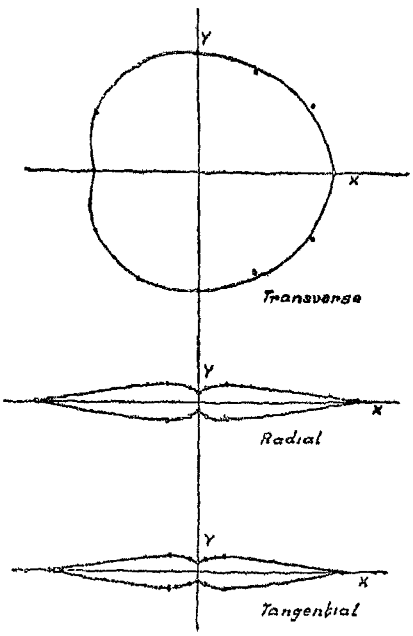


Fig No 3
Young's Modulus of Artocarpus Hirsuta

ELASTIC PROPERTIES OF WOOD

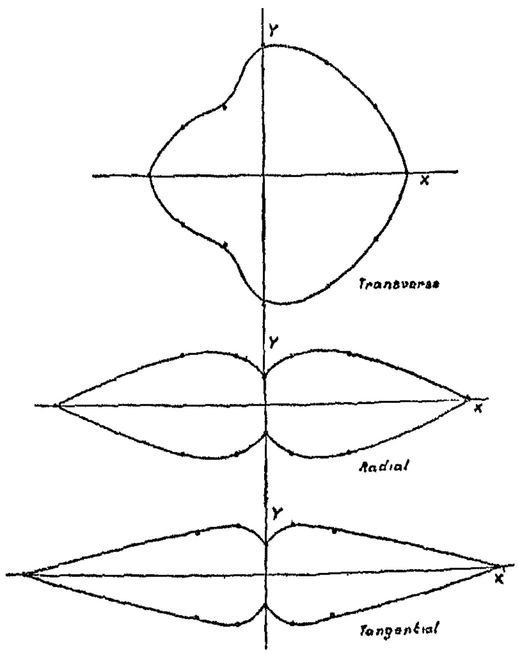


Fig No 4
[illegible]

ELASTIC PROPERTIES OF WOOD

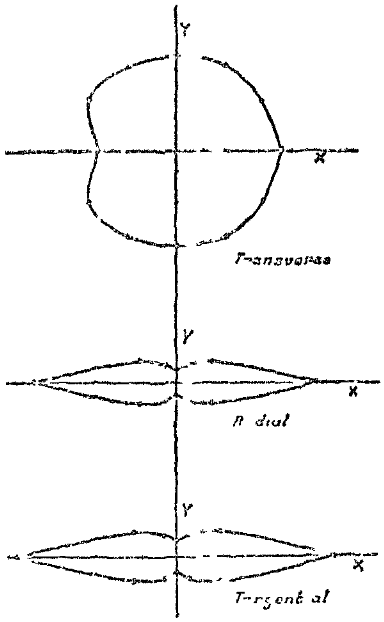


Fig No 5
Young's Modulus of Tectona Grandis

ELASTIC PROPERTIES OF WOOD

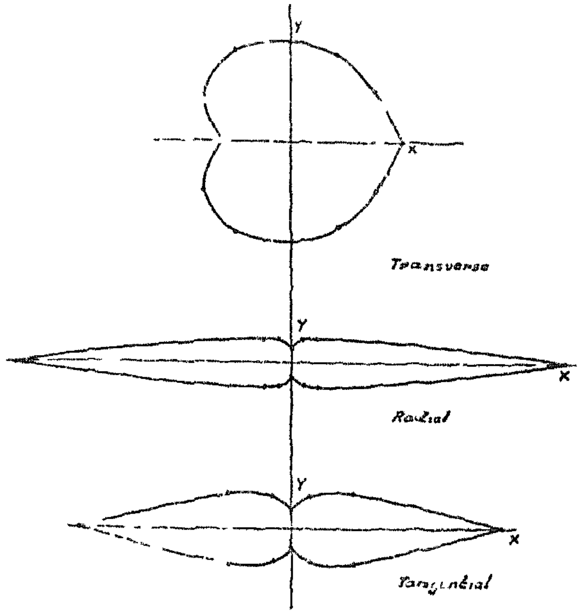


Fig No 6
Young's Modulus of Bombax Malabaricum

2 Thermal Conductivity of Timber

In the present investigation the thermal conductivity of wood has been measured in the transverse, radial longitudinal and tangential longitudinal directions for all the timbers studied in the preceding investigation Also the variation of thermal conductivity with temperature has been measured both for transverse and longitudinal sections

The experimental arrangement is that of Lees using a disc of the material about 10 cm in diameter and 4 mm in thickness cut out in the appropriate direction from the wood The flat surface was turned on a lathe and sand-paper polished to ensure good thermal contact The presence of moisture in the specimens was found to be a source of uncertainty and trouble in the experiment and so the following method was employed The specimens to be studied on a particular day were left overnight in an air-oven electrically maintained at 102°C and the apparatus for measuring the conductivity covered by a large bottomless wooden box from the top insic which were suspended two shallow beakers containing fused calc chloride The box was made of ply-boards for the sides with g front and back The top also was a board of plywood, with a l number, more than one hundred, of small holes each about 1 cm diameter The box was about 3 ft long, 2 ft wide and 3 ft high already mentioned it had no bottom and it was resting upon a sl of thick cloth spread on the table and near the bottom of each of two plywood sides was a hole about 1 inch in diameter Each of two holes was fitted with a tight-fitting thin walled glass tube, ope both ends and about 1 ft in length supported horizontally The g tubes were filled with a close packing of lumps of fused calcium cl ride This arrangement ensured that the air inside the box was over-heated during an experiment extending over eight or ten ho on account of the large number of ventilating holes at the top the same time the insuction through the two glass tubes at the bott was secured dry on account of the air being drawn through calcium chloride in the tubes The effect of this enclosed space not cause a rise of more than three or four degrees in the tempe ture of the air within with respect to the laboratory temperat outside

After the specimen had been left for nearly fifteen hours insi the air oven at 102°C, the current to the oven was cut off and t oven was allowed to cool There was, as usual, a good supply fused calcium chloride inside the oven Six hours after the switchi off of the current, the specimen was taken out and quickly transferr to the apparatus inside the box The experiment was then proceed with The cooling part of the experiment was also conducted insi the box which helped to ensure the constancy of surrounding conc tions and to eliminate the effect of wind and the disturbance cause by the experimenter

For measuring the temperature variation of thermal condu tivity in wood, the same arrangement and method were employe ccept tor the tact that the steam chamber in the Lee's apparatus as replaced with an electric heater with a flat, smooth, polished pper surface of brass, the diameter of which was the same as that of e steam heater The current supplied to the heater was regulated means of a suitable rheostat and indicated by a sensitive ammeter rmanently included in the circuit By keeping the current at a eady value for a matter of four hours, the heater reached a steady nperature which was recorded by means of a thermometer, introced into it just below the brass top A copper constantan thermouple in conjunction with a sensitive micro-galvanometer capable of tecting a temperature difference of less than half a degree ntigrade between the two junctions was used with one junction on top surface of the heater and the other introduced into the hole cupied by the thermometer when the steady state had been reached e galvanometer did not indicate any noticeable deflection thereby owing that the reading of the thermometer can be taken as equal the temperature of the top surface of the heater

The following table Nos 14 to 19 give the values of the rmal conductivities of the various woods in the three princidirections as obtained in the first experiment with the steam ater The values T_1 and T_2 represent the temperatures of the faces of the specimen while T represents the mean temperature responding to which the value of the conductivity is given conductivity given in column 7 represents the value across section given in column 1 Thus the value in the first row rizontal line) represents the conductivity across the transse section, i e, parallel to the fibres The value in the ond row represents that in a direction normal to both the ray and fibre while the value in the third row represents the conductivity direction normal to the fibre but parallel to the rays

The table Nos. 20 to 25 give the results of the temperature ation of conductivity and the curves in figures VII to IX represent results graphically

TABLF XIV

Thermal Conductivily of 'Teiminalia Tomentosa'

Direction aci oss	Diameter in cm	Thick-ness	T_1	T_2	T	Conducti cal cm
Transverse	10 75	0 37 cm	98° 0c	78° 0c	88° 0c	6 26 × 1
Radial	,,	0 33 ,,	,,	84 5c	91 3c	3 23 ,,
Tangential	,,	0 23 ,,	,,	81 0c	89 6c	4·14 ,,

TABLE XV

Thermal Conductivity of 'Teiminalia Paniculata'

Direction across	Diameter in cm	Thick-ness	T_1	T_2	T	Conducti in cal cm
Transverse	10 75	0·39 cm	98° 0c	84° 8c	91° 4c	7 17 × 1
Radial	,,	0 43 ,,	,,	77 5c	87 8c	4 37 ,
Tangential	,,	0 41 ,,	,,	79 3c	88 7c	4 75 ,

TABLE XVI

Thermal Conductivity of 'Artocarpus Hirsuta'

Direction across	Diameter in cm	Thick-ness	T_1	T_2	T	Conducti in cal cm
Transverse	10 76	0 41 cm	98° 0c	79° 5c	88° 8c	5 38 × 1
Radial	,,	0 21 ,,	,,	77° 0c	87° 5c	2 30 ,,
Tangential	,,	0 32 ,,	,,	74° 0c	86° 0c	2 85 ,,

TABLE XVII

Thermal Conductivity of 'Dalbergia Latifolia'

tion ss	Diameter in cm	Thick-ness	T_1	T_2	T	Conductivity in cal cm sec
erse	10 75	0 38 cm	98° 2c	83° 2c	90° 7c	$6\ 92 \times 10^{-4}$
	,,	0 29 ,,	,,	80° 0c	89° 3c	5 02 ,,
ıtial	,,	0 33 ,,	,,	79 0c	88 5c	4 22 ,,

TABLE XVIII

Thermal Conductivity of 'Tectona Grandis'

tion ss	Diameter in cm	Thick-ness	T_1	T_2	T	Conductivity in cal cm sec
erse	10 75	0 41 cm	98° 5c	84° 3c	91° 5c	$7\ 10 \times 10^{-4}$
	,,	,,	,,	78° 6c	88° 6c	4 69 ,,
ıtial	,,	,,	,,	79 1c	88 8c	4 87 ,,

TABLE XIX

Thermal Conductivity of 'Bombax Malabaricum'

tion ss	Diameter in cm	Thick-ness	T_1	T_2	T	Conductivity in cal cm sec.
'erse	10 75	0 38 cm	99° 0c	75° 8c	87° 4c	$3\ 75 \times 10^{-4}$
	,,	,,	,,	75 5c	87 3c	3 67 ,,
ıtial	,,	0 37 cm	,,	75 7c	87 4c	3 71 ,,

TABLE XX

Thermal Conductivity–Variation with Temp –Terminalia Tomen

Direction	Limits of Temp	Mean Temp	Conductivity cm cal sec
Along Fibre	46° 7–68° 3	57° 5c	000586
,,	67 6–103 8	85 7	·000615
,,	96 4–162 1	129 3	·000631
,,	119 7–209 7	164 2	000648
Across Fibre	49 2– 70 6	59 9	000296
,,	68 1–108 0	88·1	000315
,,	90 2–154 0	127 1	000317
,,	119·7–211 0	165 4	000337

TABLE XXI

Thermal Conductivity–Variation with Temp –Terminalia Paniculata

Direction	Limits of Temp	Mean Temp	Conductivity cm cal sec
Along Fibre	50 5– 69 5	60 0	000687
,,	70 8–106 0	88 4	000705
,,	101 2–161·8	131 5	000726
,,	128·5–220 3	174 4	000787
Across Fibre	45 3– 67 0	61 2	000514
,,	61 6–105 0	83 3	000448
,,	89 0–162 5	125 8	000488
,,	115 8–218 5	167 2	·000518

TABLE XXII

Thermal Conductivity–Variation with Temp–Artocarpus Hirsuta

Direction	Limits of Temp	Mean Temp	Conductivity in cm cal sec
Along Fibre	49 8– 68 5	59 1	000521
”	69 6–105 8	87 7	000531
”	98 5–160 0	129 3	000547
”	129 0–218 0	173 5	000563
Across Fibre	49 5– 70 5	60 0	000234
”	67 8–110 0	88 9	000229
”	92 8–164 0	128 4	000231
”	121 0–219 4	170 2	000247

TABLE XXIII

Thermal Conductivity–Variation with Temp–Dalbergia Latifolia

Direction	Limits of Temp	Mean Temp	Conductivity in cm cal sec
Along Fibre	46 0– 67 0	56 5	000628
”	66 2–107 5	86 9	000684
”	93 2–158 0	125 6	000759
”	120 2–209 0	164 6	000805
Across Fibre	52 5– 70 5	61 5	000496
”	75 0–110 2	92 6	000412
”	104 4–167 0	135 7	000375
”	144 0–231 0	187 5	000394

TABLE XXIV

Thermal Conductivity–Variation with Temp –Tectona Grand

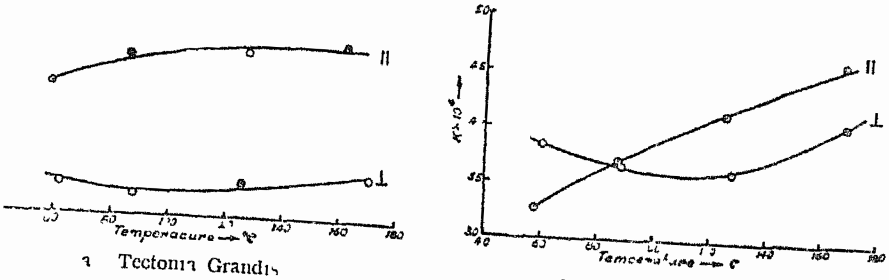
Direction	Limits of Temp	Mean Temp	Conductivit cm cal s
Along Fibre	46 8– 64 0	55 4	000674
”	68 4–102 0	85 2	000731
”	97 6–157 0	127 3	000741
”	121 0–201 5	161 3	000758
Across Fibre	45 8– 66 5	61·2	000503
”	66 2–109 0	87 6	000489
”	90 1–161 0	125 6	000517
”	11 0–222·0	170 0	000524

TABLE XXV

Thermal Conductivity–Variation with Temp –Bombax Malabar

Direction	Limits of Temp	Mean Temp	Conductivit cm cal s
Along Fibre	45 2– 69·8	57 5	000328
”	62 2–111 6	86 9	000372
”	84 1–167 5	125 8	000400
”	112 0–222 0	167 0	000465
Across Fibre	47 0– 73 0	60 0	000384
”	64 0–113 5	88 8	00037[illegible]
”	85 8–170 0	127·9	·000363
”	111 8–224 0	167 9	000408

VARIATIONS OF THERMAL CONDUCTIVITY IN WOOD WITH TEMPERATURE

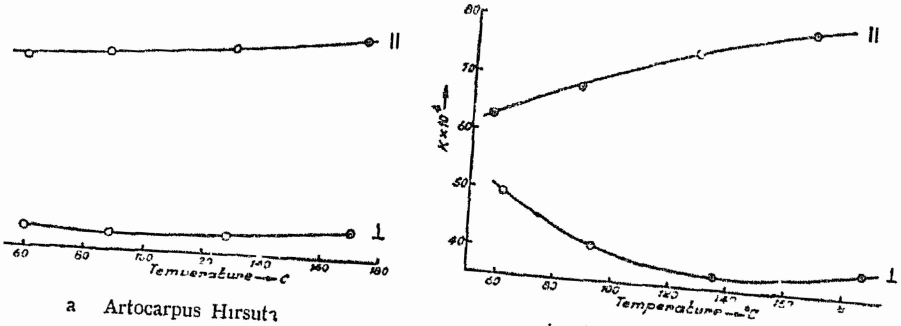


a Tectonia Grandis

b Bombax Malabaricum

FIG No 7

VARIATIONS OF THERMAL CONDUCTIVITY IN WOOD WITH TEMPERATURE

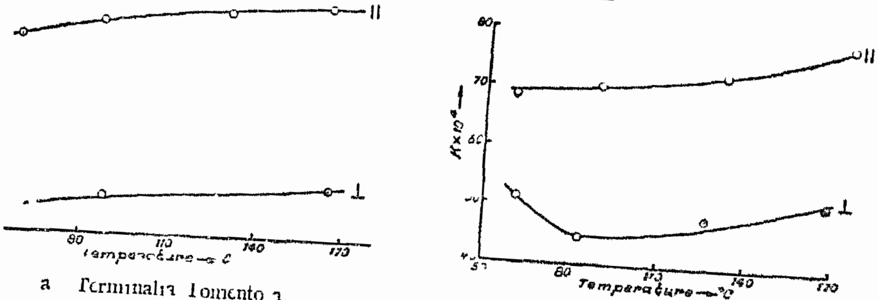


a Artocarpus Hirsuta

b Dalbergia Latifolia

FIG No 8

VARIATIONS OF THERMAL CONDUCTIVITY IN WOOD WITH TEMPERATURE



a Terminalia Tomentosa

b Terminalia Paniculata

FIG. No 9

'/

3 Thermal Expansion of Wood

For measurıng the theı mal expansıon of wood, an oŗ lever was employed to magnıfy the expansıon The mııroı stag fig 10 was supported wıth ıts fıont leg restıng on the top oi specımen and ıts ıeaı legs restıng on a hoııızontal metallıc plat clamped on to a tubular retort stand P The specımen, ın the of a rectangular rod, about 20×1×1 cm, was placed ınsı specıally constructed heater The heateı consısted of a rectan copper tube C open at both ends on whıch was wound a unı layer of 'monel' ıesıstance wıre wıth a thın leaf of mıca ınsulatın bare wıre fıom the copper tube The heatıng element was wra up ın a thıck paddıng of asbestos paste the whole aııangement was shea round wıth a wooden tube T, whıch ved to hold the heater clamped veıtı The bottom end of the specımen v was just projectıng out of the heater restıng upon the hollow base B oi ıetort stand A cuıı ent of cold water led ınto B fıom wheıe ıt flowed ınto veıtıcal pıllaı P and was led oft fıoı top to the sınk Thıs curıent of water helped to keep the ıest of appaıatus at constant tempeıatuıe v the heateı was ıaısed to dıfferent temperatuıes, so that the ch of ıeadıng obtaıned wıth the optıcal leveı was due to the expansı the specımen only A pıece of asbestos boaıd wıth a squaıe ho the centre for the specımen to pass through was placed on the ba below the heater and served to pıevent the coolıng effect oi current of water from reachıng the heateı

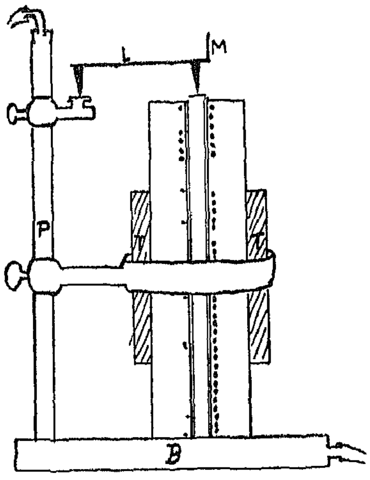


Fig 10

A prelımınary experıment was conducted to see how ıt would be necessary to heat the specımen befoıe ıt would as a unıform tempeıatuıe throughout ıts bulk. For thıs purpose a s men of 'Bombax Malabarıcum' whıch ıs known to have the poı conductıvıty was pıepaıed out of a transverse sectıon of the v narrow hole of about 1 5 mm diameter was bored along the axis of e specimen down to the middle of its length and a tiny drop of ercury was put at the bottom of the hole The specimen was then aced inside the heater and one junction of a thermo-couple, made › of two wires of S W G 40, of copper and constantan was introduced to the hole so as to keep the junction dipping in the drop of mercury the bottom The thermo-couple was carried at the end of a long in rod of 'Bombax Malabaricum' with the wires running straight ›wn through grooves on the side of the rod The diameter of the ›d was very nearly equal to the diameter of the hole in the specimen › that the rod pushed down nearly to the bottom of the hole served restore conditions approximating to those of a solid rod The her junction of the thermo-couple was in contact with the copper be of the heater and the thermo-current was read oft on a sensitive irror galvanometer which was suitably shunted in the early stages the heating and which was sensitive enough to indicate a difference less than 1°C between the two junctions when the shunt was moved It was found that, after the lapse of four hours of continu- is heating, the thermo-couple indicated an equalisation of tempera- ›re to within about half a degree centigrade between the core and ie surface of the specimen In all subsequent experiments, the ›adings of the optical lever were taken twice after the lapse of four ›urs, with an interval of half an hour between the two readings he fact that the two readings were the same served further to show iat the expansion had reached a steady value

Since it was intended to study the variation of thermal pansion with temperature, the heater was previously calibrated by issing various known values of the heating current and noting the ial steady temperatures attained within the enclosure The tem- ›rature inside the enclosure was read oft by means of a mercury iermometer suspended inside with a plug of cotton-wool stuffed into ie mouth of the enclosure to prevent convection errors The eating current was registered by means of a milliammeter with maximum range of 500 mA kept permanently connected in the ircuit Since the current it was that was adjusted to secure different temperatures and values of the current had to agree the divisions of the milliammeter scale, it was not possible to s any previously specified temperature nor strictly uniform interva temperature The temperatures resulting from suitable adjustn of the current had to be employed

In the course of the experiment, as each specimen introduced into the heater and the experiment started, almost i ably there was contraction with rise of temperature which we increasing till about 100°C It was suspected that this contra was a spurious phenomenon apparently due to the shrinkage ca by the loss of moisture on heating To test out this point specimen was left inside an air-oven previously for about six hou 102°C and then quickly transferred while hot into the cold appa and then allowed to cool inside the apparatus overnight, with mouth of the apparatus tied down with a piece of filter-paper next day the experiment was started after removing the filter-p and putting the optical lever in position A ring of cotton wrapped round the top end of the specimen which was just proje out of the heater cut off convection effects It was then noticed the specimen showed an expansion with heating from the start. process was therefore adopted in all measurements and so the va given correspond to the perfectly dry condition

The maximum temperature up to which the measurement carried out was about 200°C. since it was feared that prolor heating above this temperature might affect the nature of w Three specimens of each timber were employed for the meas ment The first belonged to the longitudinal direction, the sec to a transverse direction in a tangential plane (i e , from a flat s board) and the third to a transverse direction in a radial plane (from a quarter sawn board)

The following tables Nos 26 to 31 give the values of thermal expansion of the different woods as measured by the ab method.

TABLE XXVI

Thermal Expansion of 'Terminalia Tomentosa'

	32.0°–90°C	90°–138°C	138°–201°C
ngential Longitudinal Section			
allel to Fibre	1.80×10^{-6}	2.04×10^{-6}	3.59×10^{-6}
oss Fibre	16.60×10^{-6}	8.81×10^{-6}	3.56×10^{-6}
dial Longitudinal Section			
Across Fibre .	15.80×10^{-6}		

TABLE XXVII

Thermal Expansion of 'Terminalia Paniculata'

	31.0°–90°C	90°–138°C	138°–201°C
ngential Longitudinal Section			
allel to Fibre	2.01×10^{-6}	3.38×10^{-6}	4.99×10^{-6}
oss Fibre .	18.30×10^{-6}	7.31×10^{-6}	4.77×10^{-6}
dial Longitudinal Section			
ross Fibre .	17.20×10^{-6}		

TABLE XXVIII

Thermal Expansion of 'Artocarpus Hirsuta'

	33.0°–90°C	90°–138°C	138°–201°C
ngential Longitudinal Section			
rallel to Fibre .	2.15×10^{-6}		5.52×10^{-6}
ross Fibre .	15.70×10^{-6}		5.08×10^{-6}
dial Longitudinal Section			
ross Fibre .	14.86×10^{-6}		

TABLE XXIX

Thermal Expansion of 'Dalbergia Latifolia'

	32 0°–90°C	90°–138°C	138°–20
Tangential Longitudinal Section			
Parallel to Fibre ..	$1\ 67 \times 10^{-6}$	$2\ 97 \times 10^{-6}$	3 79 ×
Across Fibre ...	$13\ 37 \times 10^{-6}$	$7\ 01 \times 10^{-6}$	3 65 ×
Radial Longitudinal Section			
Across Fibre ..	$13\ 10 \times 10^{-6}$		

TABLE XXX

Thermal Expansion of 'Tectona Grandis'

	33·0°–90°C	90°–138°C	138°–20
Tangential Longitudinal Section			
Parallel to Fibre ..	$1\ 891 \times 10^{-6}$	$3\ 12 \times 10^{-6}$	4 61 × 1
Across Fibre ..	$20\ 660 \times 10^{-6}$	$7\ 02 \times 10^{-6}$	3 48 × 1
Radial Longitudinal Section			
Across Fibre ..	$19\ 320 \times 10^{-6}$		

TABLE XXXI

Thermal Expansion of 'Bombax Malabaricum'

	28 0°–90°C	90°–138°C	138°–20
Tangential Longitudinal Section			
Parallel to Fibre ..	$2\ 40 \times 10^{-6}$		2 58 × 1
Across Fibre .	$27\ 10 \times 10^{-6}$	$9\ 33 \times 10^{-6}$	3 88 × 1
Radial Longitudinal Section			
Across Fibre .	$25\ 30 \times 10^{-6}$		

Chapter III—THE CONSTITUTION OF TIMBER PHYSICAL AND CHEMICAL

The results of the investigations into the elastic and thermal operties of wood which have been recorded in the previous chapter ive revealed the anisotropic character of wood in such a clear and mprehensive manner that it is no longer possible to consider the rectional variation of any property as a matter of fortuitous circum-ances Indeed the large and well-coordinated variation of property ith direction in all the cases studied suggests a deep seated unifying use as controlling and determining the degree and nature of the isotropy of wood It is evident that a cause which can thus iformly influence such fundamental properties like elasticity, ermal expansion etc, should be intimately associated with the ture and constitution of wood and so, in order to be able to interpret e experimental results obtained, it would be necessary to draw on both the physical and chemical constitution of wood An attempt s been made to elucidate the constitution of timber and the results such an investigations form the subject matter of the present apter

The physical constitution of timber has been studied both m the microscopic point of view and the X-ray point of view while e chemical constitution has been studied with a view to determine e percentage composition of the major components of wood

I Micro-Structure of Wood

A Technique of Wood Sectioning

The subject of plant anatomy dealing with the nature and rangement of the ultimate constituents of wood had a long and ntroversial development during the 18th and 19th centuries and is only since the beginning of this century that the subject may said to have settled down to some definite form recognised as bstantially correct by various schools of botanists According to e commonly accepted conceptions, the architecture of all timbers lows a common plan wherein elongated tissues of various kinds are

bound together in almost parallel bundles by forces partly me
and partly physico-chemical The most important among these
are the tracheids, fibres, vessels and bast Of these the tr
are important from the point of the growth of the tree w
fibre is important from the point of view of mechanical s
The fibres are simply the post-mortem state of the trachei
the latter, due to lignification and thickening of the walls, had
their utility as transporters of food materials of the plant T
differs from the wood fibres only morphologically in that the
found outside the cambium or the active growing part of
while the fibres are within the cambium in what might st
called the stem or trunk of the tree, so that from the point of
the practical utility of timber as a building material, bast is
little significance The vessels, also called pores, are long tu
quite thin walls, which are found throughout the stem, whic
to transport water and other fluids during the life of the t
which become places of mechanical weakness in the dead
Obviously the greater the size and number of these vessels th
will be the mechanical strength of the timber

Thus from the point of view of the present investiga
fibre is the most important factor while the study of the
distribution of the vessels will indicate their general effec
conclusions drawn from the study of fibres Evidently ther
is a matter of great importance to have a correct knowled
structure of the wood for an interpretation of its physical pr
The methods of sectioning timber in order to study its
constitution have been developed by various workers but in
methods, laborious and protracted preliminary treatment of t
in various liquids like nitric acid, hydro-fluoric acid, alcohol,
canadabalsam or collodion is necessary followed by various
of staining Whatever might be the chances of chemical n
being altered by these processes of pre-treatment, it is evi
in the case of wood, a material characterised by strong
powers and great moisture absorption with consequent large
in physical properties, it would be preferable to avoid such

nary treatments Kisser[40] in Germany and Crowell[10] in America almost simultaneously developed a method of sectioning without pre-treatment, which consists in allowing hot water or wet steam to play upon the specimen while it is being microtomed This method though quicker and less likely to cause large changes in the structure, is not quite suited to the present investigation on account of the fact that the specimen during cutting is kept hot and wet, two conditions which contribute to large plastic deformation in wood So after various attempts, the following direct method of sectioning was employed and gave thoroughly satisfactory sections of all the woods studied

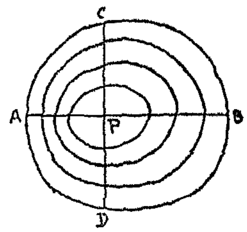


FIG 11

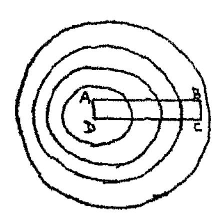


FIG 12

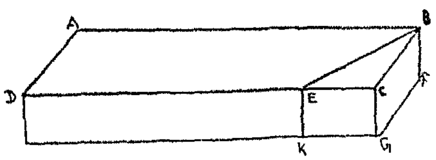


FIG 13

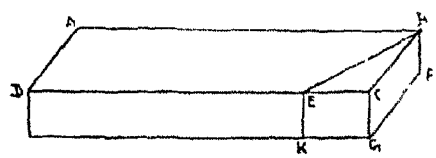


FIG 14

The most important factor for successful sectioning of timber, even of the hardest kind, without previous physical or chemical treatment is in getting specimens cut out in the proper manner for mounting on the microtome The illustration, fig 11, shows a transverse section of timber and out of this transverse section, a piece like ABCD is cut off In fact one of the test-pieces employed in the measurement of Young's modulus in the transverse section served very well for the purpose AB was about 3 cm long while BC was about 1 5 cm long The thickness BF, fig 13, at right angles to AB and BC was about one cm The position of ABCD was so chosen that BC formed part of one of the annual rings of growth, so that a section parallel to BC and perpendicular to AB would be truly a tangential longitudinal section A line BE inclined at an angle of from 30° to 60° with AB was marked on ABCD and the right angled prism BCE was cut off with a fret-saw The harder the wood, the smaller was the angle ABE This wedge-ended specimen ABED was clamped in the specimen holder of a microtome with the edge BF projecting about half a cm from the holder The specimen holder was so adjusted that the edge BF was vertical while the edge AD was horizontal and in the plane of movement of the microtome Thus the knife whose edge was set parallel to the plane of motion of the instrument, took off truly tangential longitudinal sections out of the specimen

For radial longitudinal sections, the prism BCE was mounted in the holder with the edge BF vertical and the edge CE horizontal and parallel to the edge of the cutting knife

For getting transverse sections, a rectangular parallelopiped ABCDLGFM (fig 14) was chosen from a longitudinal section with AB parallel to the fibre AB was about 3 cm in length while BC and BF were each about 1 cm A line BE at an inclination of 30° or less with AB was marked and the prism BCE was cut off The wedge-ended piece ABED was mounted on the microtome with BF vertical and AD horizontal and parallel to the knife-edge so that truly transverse sections were cut off by the razor

The microtome employed was a large one of the Leitz-Wetzlar pattern with a very hefty razor and the automatic cross-feed was adjustable for various thicknesses from 1 to 25μ Most of the sections prepared for the present investigation were about 5 to 6μ in thickness The first few sections being too narrow were discarded and the best out of the subsequent fifty or sixty sections were chosen No kind of lubricant or wetting was employed The sections, as they fell from the razor, were collected in a small watch glass and by examining with a low power pocket lens, a clean unbroken section was transferred straight on to a slide and covered with two drops of a thin 2% solution of Canada balsam in xylol. The section, which

times curled up during the cutting, straightened out natur-
e application of the balsam solution and immediately after-
cover slip was placed on the flat-specimen and firmly
against it so as to squeeze out the balsam solution to the
minimum inside The slide was then left on the outside of a
a temperature of about 40°C for about three or four days,
time it dried up quite well In the case of 'Dalbergia
and 'Terminalia Tomentosa' a few drops of absolute alcohol
o the section before the addition of the balsam solution
) dissolve away much of the colouring matter leaving the
lear and transparent

B RESULTS AND CONCLUSIONS

ioto-micrographs, Plates I to VI, of these sections were
ith a Winkel-Zeiss Petrological microscope Class VI M
ctures were taken with unpolarised light while for some
larised light with Nicols set at various angles of crossing was
i to secure the largest amount of details in the photographs
ce of illumination was a glass-mercury lamp whose light was
hrough a green filter The photographs were all taken on
ipid panchromatic plates at two magnification ratios, the first
and the second about 120 The actual magnification was
t by photographing on the same scale a standard Carl-Zeiss
From the negatives thus obtained, the fibre dimensions
asured and the reduced values i e, the actual dimensions of
are given in the following table It is, ofcourse, impossible
any uniformity of size among the fibres so that the figures
the mean of at least thirty measurements for each The
mensions of individual members might vary within about
ie mean value on either side Plates are photographs of the
obtained

n examination of the Photo-micrographs reveals very striking
istics of the structure of the various timbers While the
'Terminalia Tomentosa', 'Terminalia Paniculata', 'Arto-
Hirsuta' and 'Tectona Grandis' are of the same order of

TABLE XXXII

	Name of Specimen	Length of Fibre mm	Shape and size of Fibre mm.	Thickness of Fibre Wall mm
I	Terminalia Tomentosa ..	0 65	○ 015	0 003
II	Terminalia Paniculata ...	0 55	⬭ 025 × 015	0.005
III	Artocarpus Hirsuta	0 80	▭ 040 × 030	0 007
IV	Dalbergia Latifolia .	Twisted 0.20	Irregular 020	005 – 0 008
V	Tectona Grandis ...	0 48	⬭ 018 × 010	0025
VI	Bombax Malabaricum .	0 50	○ 055	008

magnitude in length and cross-section and all of them lie with their entire length in the same plane, their distribution and arrangement are different in the different timbers In 'Terminalia Tomentosa,' the fibres run continually changing from side to side of the numerous medullary rays that occur in great profusion in the timber with the result that any one fibre is distinctly of a wavy form and associated with at least half a dozen groups of medullary rays Consequently planks of this timber taken out of a tangential longitudinal section will be well adapted to resist splitting or cracking This advantage is however off-set to some extent by the fact that the vessels are large and diffusely distributed liberally throughout the section and each vessel is surrounded by a layer of soft tissue Further the transverse diameter of the pores is quite often more than twice the distance between adjacent medullary ray-bundles so that thin planks in the tangential plane are liable to crack due to failure at the vessels It is, therefore, necessary to use fairly thick planks where durability is a primary consideration This explains the unsuitability[41] of this timber for rotary veneer cutting, though, on account of its dark colour and close grain with corresponding capacity for taking a high degree of polish, it can be utilised in veneer work if sawed or sliced.

In 'Terminalia Paniculata' the fibres are long and straight and distinctly elliptic in section The medullary rays are of irregular shapes and sizes and also irregularly distributed The vessels are large, numerous and diffuse and surrounded by soft tissue On account of the number, shape and distribution of the medullary rays, quarter sawn planks are likely to present a better appearance than flat sawn ones and are also likely to polish better

'Artocarpus Hirsuta' has the longest fibres of all the timbers studied in the present investigation and the fibres are wavy in shape and more or less rectangular in section The fibres bend round the medullary rays which are not quite so numerous as in the previous varieties The vessels are of medium size, irregularly shaped and arranged in rings characteristic of ring-porous wood The long fibres, the wavy medullary rays and the comparatively small pores facilitate easy working of the timber and also enable it to take a high degree of polish The comparatively scanty amount of medullary rays enables the wood to split easily in tangential planes and is therefore widely applied in the manufacture of splints and match-boxes It is also likely that the trunk will be suitable for rotary veneer cutting

'Tectona Grandis' is also of the ring-porous type with rather small vessels whose diameters are often less than half the distance between the rays The fibres are long and straight and of elliptic section of fairly uniform size The medullary rays are straight, uniform and in large layers in a direction parallel to the stem so that quarter sawn planks present a very beautiful silver grain The wood is quite close-grained and so takes a high polish Structurally it is admirably suited for rotary veneer cutting for plywood making Since both the fibres and the rays are running almost dead straight, the timber is liable to split asunder easily under mechanical shock, a defect which should be guarded against especially in the design of railway carriages for which the timber is greatly employed

In 'Dalbergia Latifolia' the structure is distinctly different from all the previous ones The fibres though long are spiral shaped and strongly interlocked The medullary rays are in small lens shaped clusteis extiemely numeious and ex naiily uniformly distiibuted The vessels aie thin and scar occasionally contain some iesinous oi ciystalline mateiial On of the spiial shape and stiong interlocking of the fibres, the makes excellent turning material and is used foi all kinds o mental carving It is next to impossible to employ it for iotaiy cutting but the sawed veneei is veiy often employed on accour beautiful colour of the polished wood It will make excelle handles especially for the caipenters' chisel since its stiuc specially suited for shock-iesisting

'Bombax Malabaricum' stands in a class distinct fi iest It has piactically no fibres, strictly so called The mec strength is supplied by the wood paienchyma tissues, whi developed a septate structure foi increased stiffness Eacl has four compartments and is fusifoim in shape A tangentia tudinal section piesents an extiaordinaiily beautiful app consisting of very regulaily ariianged spindle shaped parei tissues, each quadiu-septate and of an almost unvarying s shape The ratio of length to cioss-section of the tissues much smallei in this wood than in any other while the c thickness is almost of the same order of magnitude as i timbers The medullary rays aie stiaight and iegulai an uniformly distributed The vessels aie scanty and of medi where they occur On account of its non-fibious natuie the very easy to work, especially, on the lathe and is employed making Its lightness and easy workability make it part suitable for making matches and the compaiative scarcity pores iender the matches free from the defect of back-firing ever on account of the veiy weak cell-walls and the large cell-cavities the wood is specially inviting to boiing insects large open stiuctuie of the timbei offering as it does plenty space inside rendeis the wood a good heat insulator and if a preservative can be employed to keep off boiers, the wood wi excellently for thermal insulation

2. X-RAY STUDIES OF TIMBER

The investigation of the ultimate architecture of matter is capable of yielding very valuable information on such structural properties as elasticity, tensile strength etc, which depend upon the number, order and linking of the various atoms and molecules that make up the material Such an investigation to be of maximum utility is best undertaken in the case of simple substances where the order and disposition of the atoms can be calculated from the observations comparatively easily Wood on the other hand is such a complicate mixture of intrinsically complex substances that it is a matter of very great difficulty to interpret the results of such an investigation It is why an X-ray investigation of wood did not achieve much progress till after the technical interpretation of X-ray pictures had been elucidated by a large amount of work on simple inorganic crystals

Ambronn[8] in 1917 first suggested the examination of wood by means of X-rays for its crystalline constituents and his suggestion has been followed up by a number of workers As already mentioned, the most important work in this connection is that of Meyer and Mark who not only established the crystalline character of cellulose in wood but made quantitative measurements of the unit cell and its orientation For obvious reasons, however, their work was confined to European timbers only A similar piece of fairly comprehensive structural analysis of wood for Japanese timbers has been done both by the X-ray and optical birefringence methods by Nagasawa[47] The author is not aware of any X-ray studies of Indian timbers till Nilakantan[21] investigated teak wood at Bangalore in 1937 By a series of pretreatments and successive eliminations of different constituents of wood Nilakantan has made a valuable contribution to our knowledge of the structure of teak-wood He has also been able to establish the amorphous nature of Ritter's lignin constituting the middle lamella in wood Farr has made a study of the structure and constitution of plant cell membranes including cotton and wood fibres both by the X-ray and optical methods after various degrees of swelling and a brief report of his conclusions can be found in 'Nature'[42] Re the state of knowledge on cell-wall structure in plants, Frey ing[43] has critically examined the conclusions drawn by X-ray and swelling methods He has pointed out the great possib X-ray investigations of timber both on the quantitative and th tative sides Even when quantitative measurements are not n an X-ray investigation is capable of giving so much informatio structure of matter necessary for the elucidation of its physical ties that in the present investigation an X-ray study has been m all the Indian timbers whose elastic and thermal propertie already been studied

The timbers were not given any pre-treatments exc extraction with an alcohol-benzene mixture The specimen all taken from the Summer-wood portions of the tangential sec the various timbers, in the form of small pieces about a cm in and a mm or so in cross-section These pieces were extrac six to twelve hours with a mixture of alcohol and benzene The then dried and exposed with their tangential sections placed to the incident X-rays Molybdenum K-radiation was employe tube being run at 12 mA and 45 kv The period of exposu one hour and was found to be the most satisfactory one for k down to a minimum extent background scattering while, ho bringing out the crystal scattering in sufficient intensity In th of 'Tectona Grandis', in addition to the alcohol-benzene ex specimen, a picture was also taken with a specimen taken ou piece which had been used in the thermal experiment and whic remained at about 200°C for about ten hours, so that any chan to the prolonged high temperature can be detected The diagrams of the various woods are given in Plates VII & VIII

An X-ray diagram of wood is capable of giving us valuable information regarding the orientation of the ce molecules in the fibres even though no measurements are ma deduce the atomic spacing in the crystal lattice If the ce molecules are all arranged parallel to the chain-axis a fibre p with definite spots is obtained A regular arrangement in a spiral form round the fibre-axis produces a lengthening of the spots in the fibre pattern resulting in crescent shaped spots A random orientation of the crystallites gives rise to halos or rings in the pattern Besides, the presence and quantity of amorphous material in wood are revealed by the appearance and intensity of general background illumination in the picture

In the light of the above considerations it is now possible to gather some information on the structure of the various timber studied All the timbers have given diagrams with unmistakable spots and rings, thus revealing that the cellulose crystallites while following up a regular arrangement to a great extent are not perfectly well-orientated The relative brightness of the spots and rings is a fair index of the proportion of well-orientated to randomly distributed cellulose crystallites From this point of view, 'Dalbergia Latifolia' and 'Tactona Grandis' show very bright spots and very faint rings showing that a very large bulk of the cellulose is present in a well-orientated state The spots in 'Dalbergia Latifolia' have got an angular width greater than those in any other timber thus indicating a spiral arrangement of cellulose in this wood This spiral arrangement on a grosser scale is also revealed by a photo micrographic study of this wood In 'Artocarpus Hirsuta' there is apparently a large amount of disorientation of the crystallites, as evidenced by a large relative intensity of the rings The angular width of the spots given by 'Terminalia Tomentosa' is very small showing that when the cellulose is arranged at all, it is arranged perfectly parallel to the fibre-axis, while the presence of the rings indicates the existence of a certain amount of randomly distributed cellulose 'Bombax Malabaricum' has given weak spots and a large number of uniform rings on a diffuse background This shows that a large proportion of the cellulose in this wood is randomly distributed The diffuse scattering given by this wood is interesting in that usually diffuse scattering is due to amorphous material From chemical analysis this wood is known to contain only a very small percentage of lignin, it is very likely that the diffuse scattering due to the large hemi-cellulose content of this wooc thus appear to be definite evidence of the usually acc nature of hemi-cellulose In conclusion, a compar Plate VII and fig 9 in Plate VIII indicates no great patterns It would thus seem to confirm the conclu cally established, that prolonged heating at 200°C any marked changes in the wood.

3 THE CHEMICAL CONSTITUTION OF T

Wood is an intimate aggregate of a large nu materials of widely different composition and p common feature of almost all the constituents of w resistance offered to the action of common chemic the consequent difficulty of arriving at any def regarding their nature and proportion Also it ve that several of the constituents have closely allied re particular reagent so that it is very difficult to s constituents On account of these difficulties much on the chemical constitution of wood was conc percentage composition of hydrogen, oxygen, car in wood rather than with the nature and proportion constituents of wood

Most of the pioneering work on the chemical is due to the French school headed by Payen[44], F during the middle of the last century By the end other schools of chemists in England, Germany and A ed similar work Cross and Bevan[46], Willstater Klason[48], Schulze[49], Dragendorf[50] & Dore[51] are a more important workers connected with the Chemi these, Cross and Bevan and Willstater and Zechi in studying in great detail, methods of isolatioi structure of some of the major constituents of making a complete analysis of all the constituents other hand, Ritter and Fleck[52] of the Forest Pı made an extensive study of the total analysis of

PHOTOMICROGRAPHS OF WOOD SECTIONS

Terminalia tomentosa (No. [illegible]—*Continued*)

a Transverse Section

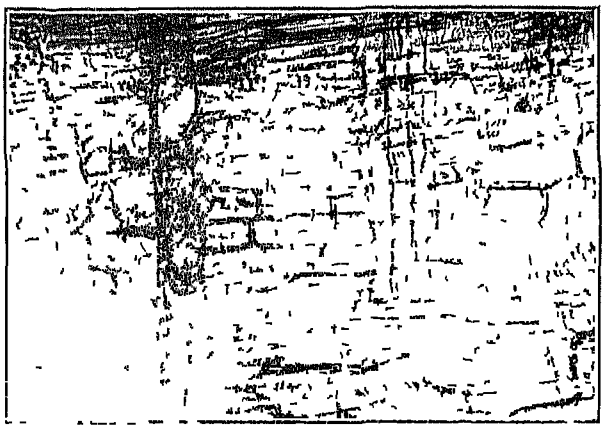
b Radial-Longitudinal

c Tangential Longitudinal

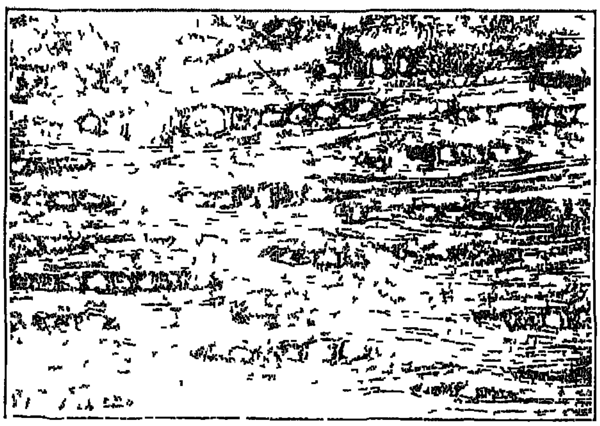
PHOTOMICROGRAPHS OF WOOD SECTIONS

Terminalia Paniculata (N O —*Combretaceae*)

a Transverse Section



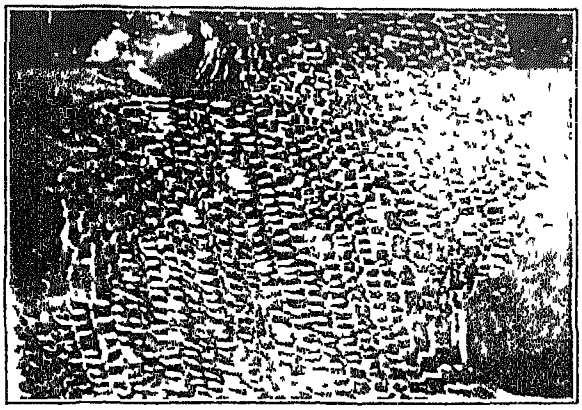
b Radial-Longitudinal



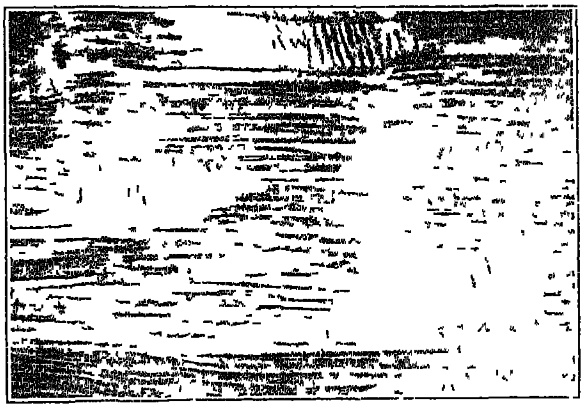
c Tangential-Longitudinal

PHOTOMICROGRAPHS OF WOOD SECTIONS

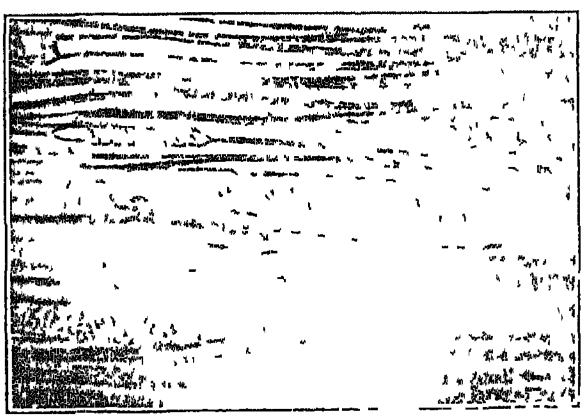
Artocarpus hirsuta (X [illegible])



a Transverse Section



b Radial-Longitudinal

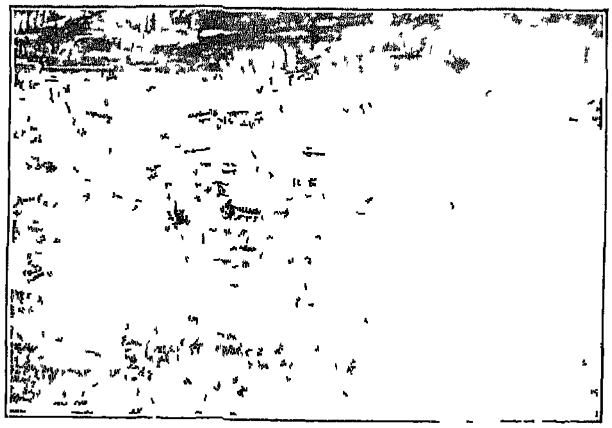


c Tangential Longitudinal

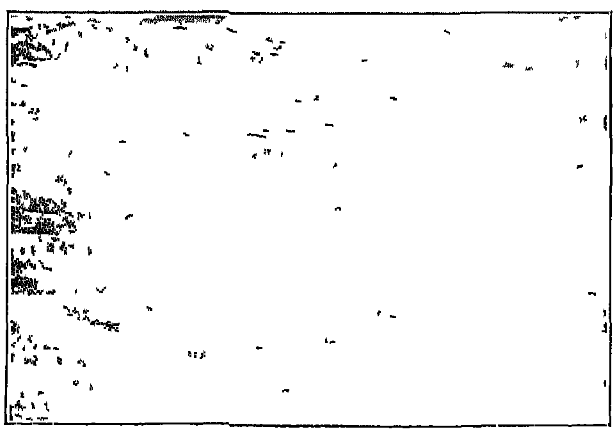
PHOTOMICROGRAPHS OF WOOD SECTIONS

Dalbergia Latifolia (N. O.—*Leguminosae*)

a Transverse Section



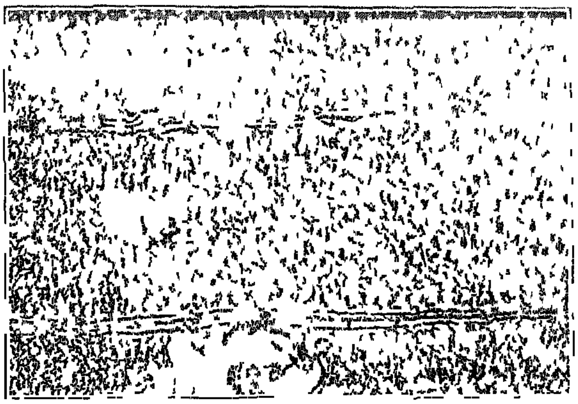
b Radial-Longitudinal



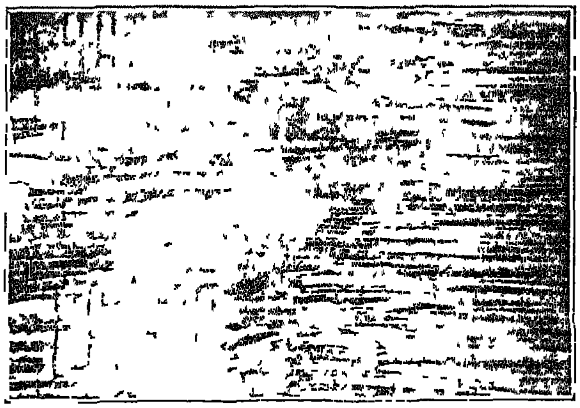
c Tangential Longitudinal

PHOTOMICROGRAPHS OF WOOD SECTIONS

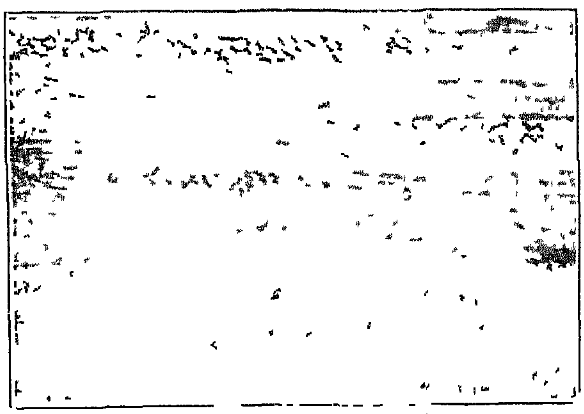
[illegible] ([illegible])



a. Transverse Section



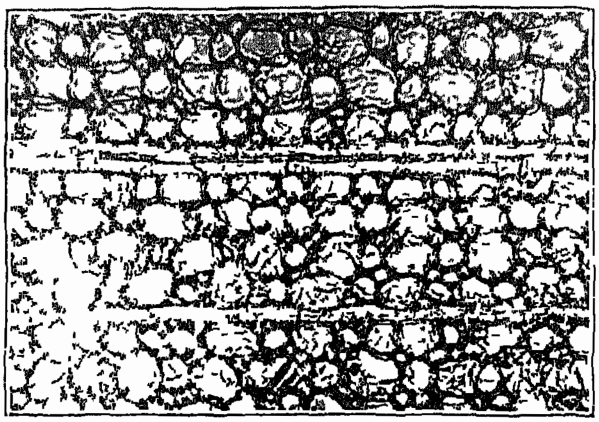
b. Radial Longitudinal



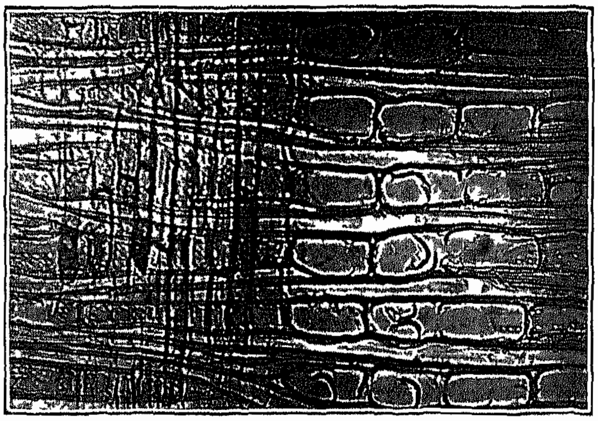
c. Tangential Longitudinal

PHOTOMICROGRAPHS OF WOOD SECTIONS

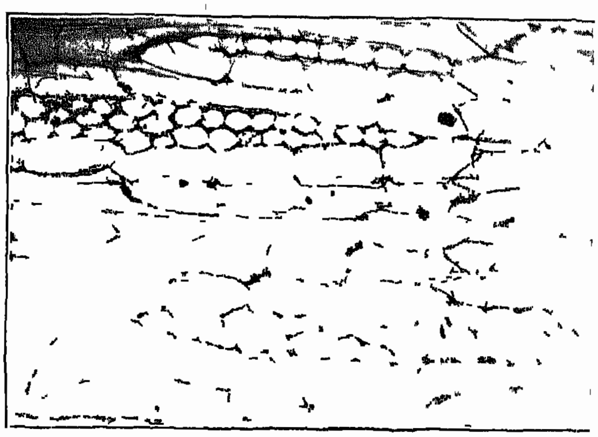
Bombax Malabaricum (N O — *Malvaceae*)



a Transverse Section



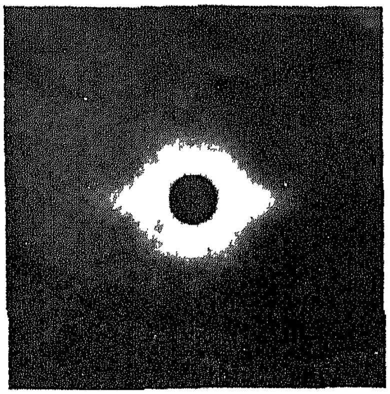
b Radial-Longitudinal



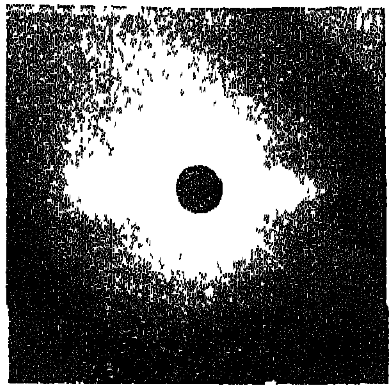
c Tangential-Longitudinal

X-RAY PHOTOGRAPHS OF WOOD

X-rays perpendicular to Fibres



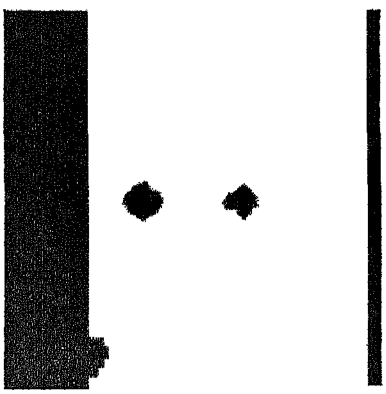
1 *Terminalia Tomentosa*



2 *Terminalia Paniculata*

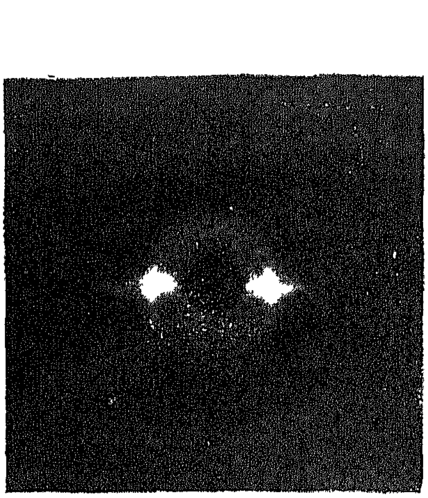
3 *Artocarpus Hirsuta*

4 *Dalbergia Latifolia*



5 *Tectona Grandis*

6 *Bombax Malabaricum*



7 X-ray diagram of 'Tectona Grandis' after heating

timbers according to a scheme of work started by Schorger while a similar kind of complete analytical work has been done for European timbers by Konig and Becker[53]

As a result of such extensive work on the methods of chemical analysis a certain amount of well-established systematic knowledge on the constitution of timber has been obtained There is still a large amount of uncertainty, however, as to how the constituents are actually assembled in the gross timber, whether they are chemically combined with one another or whether they are held up as adsorption or mechanically assembled layers of one upon another The main constituents of wood in order of abundance can be broadly divided into three groups (1) the polysaccharide carbohydrates, (2) lignin and (3) a group of miscellaneous substances like oils, fats, resins, essential oils, pigments, tannin, certain alkaloids and inorganic salts

The polysaccharide carbodhydrates which form nearly 65 to 70% of the bulk of timber are the condensation products of two or more molecules of hexose or pentose sugars with elimination of water and naturally yield the corresponding monosaccharides on hydrolysis by suitable methods The most important of these polysaccharide carbohydrates in timber is cellulose which is the disaccharide of glucose, accounting for as much as 50% by weight of timber The next in order of abundance is an ill-defined group of substances classified generally as 'hemicelluloses' These are the condensation products of hexose other than glucose with a pentose These substances contain in addition to the sugar groups an acidic part usually of the glucuronic and galacturonic acids and are therefore sometimes also called poly-uronides Pectic substances (mainly pectose), gums and mucilages also come under this category though their occurrence is not general and even when present, their proportion is very small

Lignin which forms 25 to 30% of the weight of most timbers is chiefly the incrusting substance on the cell-wall of woody fibres It is a very complex compound, highly polymerised, whose formula has been given differently by different workers according to the methods employed for its isolation and analysis Generally it is agreed that lignin is a compound containing unsaturated linkages capable of combining with halogens and sulphur dioxide to form additive compounds The lignin which is present in all timbers to a greater or a smaller amount, is believed to be an adsorption product on the cell-wall to some extent and a structural member to some extent, maintaining a honey-comb like structure throughout the wood

The third class of substances present in wood usually do not amount to more than about 5 to 10% of the total weight and are mainly responsible for the characteristic smell, taste, and colour of timber

A detailed chemical analysis of timber is of very little interest for purposes of this present investigation which is concerned chiefly with the elucidation of the mechanical and thermal properties of timber and for which a proximate knowledge of the proportion of the major constituents of wood would be quite sufficient An estimate, however, of the major constituents of wood involves directly or indirectly removal of the minor constituents and in the course of the analysis it has been possible to obtain a rough estimate of their amounts also The actual methods employed in the present investigation for the estimation of cellulose and lignin in wood have been arrived at as the most satisfactory compromise between the advantages and disadvantages of the several methods usually available for the purpose The methods fall into distinct stages of operation and are designated by a, b, c, d and e in the following

(*a*) The wood was first of all reduced to powder by sawing it with a circular bench saw of about 8 inches diameter and running at about 200 R P M and all the saw dust including the fine dust was collected and sieved through a 60 mesh sieve All that passed through the sieve, i e , the fraction designated as 60-sample by Cohen and Mackney[64] was taken up for the analysis This powder was kept in an air oven maintained at 102° for a period of 18 hours and while still in the oven, about 20 gms of it were transferred into a previously weighed stoppered weighing bottle which was then placed open inside a desiccator to cool When quite cool, the bottle was well-stoppered, taken out of the desiccator and weighed. Thus a known quantity of a perfectly oven-dry sample was taken This was next extracted with a mixture of alcohol and benzene in a Soxhlett apparatus for eight to twelve hours and in the case of rosewood, the period of extraction was extended to twenty-four hours The extracted residue was carefully washed with alcohol into a Buchner funnel fitted with a thick, close-grained filter-paper, washed with two or three changes of alcohol and finally dried in the air oven for about an hour

(*b*) The dry specimen was next completely transferred into a 500 c c conical flask and covered up with about 300 c c of distilled water The flask was fitted with a reflux condenser and the water was kept steadily boiling for about two hours Afterwards the substance was filtered out in a large funnel with a tared fluted filter paper under suction while the water was still hot The residue in the funnel was repeatedly washed with hot distilled water till the filtrate running out of the funnel did not show any turbidity The filter-paper with the substance was next allowed to dry in the oven for about six hours and then weighed The loss of weight of the substance on its original oven-dry weight represented the amount of resin, fat, oil, essential oil, pigments, tannins, gums and any hot-water soluble inorganic salts present in the wood

(*c*) At this stage it was considered advisable to remove the hemi-celluloses also, since, according to Norman and Jenkins[55] the presence of hemicellulose gives a spurious over-estimate of the lignin content during the subsequent hydrolysis of cellulose for the estimation of lignin For this purpose the oven-dry sample obtained at the end of operation 'b' was extracted for two hours with 250 c c of 1% caustic potash solution with reflux condenser The residue, as before, was filtered under suction through a fluted tared filter-paper and washed with hot water twice or thrice and then with a very weak solution of acetic acid and again with hot water till the filtrate was not giving any evidence of acidity The filter-paper with the residue was left to dry in the air oven for six hours and then weighed The loss of weight calculated on the original oven-dry sample gave the hemicellulose content of wood (*d*) The sample as obtained at the end of operation 'c' was the starting material for the estimation of cellulose and lignin Cellulose was estimated by the acid hypochlorite and sulphite method of Norman and Jenkins[56] by starting with two lots of about 2 and 3 gms respectively in separate apparatuses so that one experiment acted as a check upon the other In the case of 'Bombax Malabaricum' two chlorinations were found enough while for the other woods four to five chlorinations were necessary The cellulose obtained in all the cases was quite white in colour and after thorough washing with hot water was dried in the oven for six hours and then weighed The percentage was calculated on the original oven-dry sample

(*e*) For the estimation of lignin also two simultaneous lots of about 2 and 3 gms of the sample obtained in 'c' were taken and the lignin was estimated by the method of Ritter, Soborg and Mitchell[57] with 72% sulphuric acid for two hours at 20°C followed by dilution to 3% and hydrolysis with a reflux condenser for about four to five hours The lignin left behind was washed free of acid for a long time under suction in a Buchner funnel with a tared filter paper, finally dried and weighed and the percentage was calculated on the original oven-dry sample

In the case of the last three timbers viz, 'Dalbergia Latifolia,' 'Tectona Grandis' and 'Bombax Malabaricum', the analysis by the above methods was also conducted with specimens that had been used in the thermal experiments and which had been maintained for prolonged periods at about 200°C to see if any change in composition had been effected by the prolonged exposure to the high temperature The results are given in the following table.

Conclusion

Remembering that the purpose of the analysis was only to determine the proximate percentage of the major constituents of wood and also the fact that all these methods of wood analysis do not claim to give a better accuracy than within about 2%, no great stress can be laid upon the sum of the components not being equal to 100%

TABLE XXXIII

Chemical Composition of Wood

No	Name of Timber	Alcohol-Benzene Hot-water Extractives	1% KOH Extractives	Cellulose	Lignin
		%	%	%	%
1	Terminalia Tomentosa	5·2	10·3	51·8	32·0
2	Terminalia Paniculata	6·1	11·7	54·1	27·0
3	Artocarpus Hirsuta	5·0	9·8	52·8	29·0
4	Dalbergia Latifolia	8·7	8·1	49·2	36·0
	,, after heating	4·6	7·0	50·0	36·0
5	Tectona Grandis .	4·4	11·2	52·2	32·0
	,, after heating	3·4	9·6	53·4	34·0
6	Bombax Malabaricum.	1·5	14·2	73·8	7·0
	,, after heating	1·4	10·1	72·0	6·0

The lignin content of 'Bombax Malabaricum' is extraordinarily small, as low as 7% while its cellulose content is correspondingly extraordinarily large making up nearly three-fourths of the wood Also its hemi-cellulose content is greater than that of any other wood In fact, the poly-saccharide carbohydrate part of this timber amounts to 90% of its weight Biochemists have observed that decay in wood is started by a degradation of the hemi-cellulose by a fungus attack which rapidly spreads on to the cellulose part and eventually to the lignin part also The large hemi-cellulose and cellulose content of this wood is quite obviously the cause of its rapid attack by various borers and its quick decay when exposed to specially moist air The trouble is aggravated by the additional circumstances that lignin, which is considered to confer hardness and protection against decay in wood, is present in this timber to a very small percentage only It would

appear that a profitable method of preserving this wood, w
quite valuable for its thermal insulation properties, will be to
removing away the hemi-celluloses by an extraction with
alkalis

The effect of prolonged heating on the chemical na
wood has affected the amount of alcohol-benzene hot water ext
due evidently to the loss of essential oils and some of th
volatile oils and easily fusible resins while the cellulose an
content is fairly unaffected The observations in the case of "
Grandis' are interesting Among the hard-woods, this wood
the least amount of alcohol-benzene extractives but while 'D
Latifolia' has lost nearly half of these extractives 'Tectona Gra
lost less a fourth of it, due to heating for a prolonged period a
This would indicate that the volatile essential oil content of th
is fairly small while the oils, which this wood is known to cont
preservative against termite attack, are fairly non-volatile

In the case of 'Bombax Malabaricum', the effect of hea
affected the hemi-cellulose content to some extent while the ot
stituents are fairly unaffected It should however be pointed
total after heating is considerably short of 100% and it should
tioned that in the course of the analysis of this wood after heat
in the hydrolysis of cellulose and the chlorination of lignin, the
contained small particles of a gritty black substance, which v
probably carbon produced by a partial caramelisation of this w
to heating There is reason, therefore, to believe that this w
suffered somewhat by the prolonged heating at 200° while th
woods had not suffered to any appreciable extent

IV CHAPTER—PROPERTIES OF CELLULOSE AND L

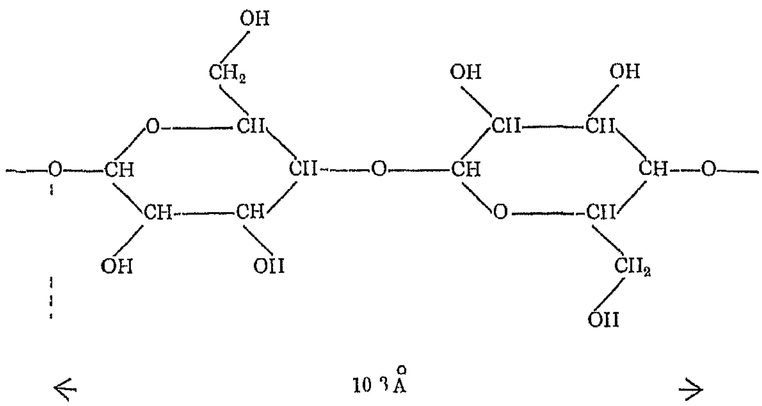
1 CELLULOSE—ITS STRUCTURE AND PROPERTIES

Cellulose constitutes quite half and sometimes even m
half the bulk of almost all timbers and is the chief frame-work
in all of them, giving them a form and mechanical strength
in more or less a pure state in the seed-hairs of the cotton

the fibres in the stem of the flax and hemp plants. About 90% by weight of the cotton seed-hair is pure cellulose while the hemp fibre consists about 70% of its weight of pure cellulose. The linen prepared from the flax stem is almost pure cellulose. In the pure state it is a bright white substance with a large avidity for water. While absorbing moisture it swells up to some extent but is quite insoluble in water. It is chemically very inert and resists ordinary organic solvents. Dilute alkali even when hot has no action upon it but hot concentrated solutions cause the fibres to swell and if kept stretched during the swelling, the fibres acquire a glossiness which is retained even after the removal of the alkali. Such treatment of cotton, discovered by Mercer, is technically very much employed in manufacturing what is known as mercerised cotton which has a silky appearance. Strong mineral acids dissolve cellulose with partial or complete hydrolysis producing simpler substances down to glucose.

The structure of cellulose has formed the subject of an extensive series of investigations by chemical and X-ray methods. Among the more important investigators on the chemical side should be mentioned Staudinger[58], Haworth[59], Freudenberg and Friedrich[60], Willstater and Zechmeister[61], Hess[62] and others and on the X-ray side should be mentioned the names of Mark, Meyer, Ritter, Astbury, Clark, Sponsler[63], Sauter[64] and others. Except for Sauter all the other investigators are agreed upon a common structure of cellulose according to which the unit of structure is the cellobiose unit ($C_6H_{10}O_8$) formed of two glucose residues joined up by oxygen atoms and the cellulose molecule is considered to be a long chain of these cellobiose units joined up again by oxygen atoms to each other. The difference between this view and that expressed by Sponsler and Sauter concerns only the size and shape of the unit cell in cellulose. According to these two investigators, the unit cell in cellulose is orthorhombic containing four molecules (i.e., cellobiose units) per cell while the other opinion favours a mono-clinic structure with two molecules per cell. In a note added to Sponsler's Publication in 'Nature', Bragg[65] shows how Sponsler's ideas are not far different from the commonly accepted ones except in the number of molecules per cell Regarding Sauter's results, Meyer[66] considers that Sauter's interpretation of his experiments is not justifiable

Taking therefore the more commonly accepted structure of cellulose, the following formula represents a molecule of cellulose



The calculation of the Young's Modulus of this structure parallel to the chain-axis has been carried out by Meyer and Lotmar[67] on the basis of bond strength derived from Raman Spectra and shows very good agreement with experimental values

The author is not aware of any determination of the Young's Modulus of cellulose in a direction normal to the chain-axis The experimental determination of this quantity will be rather difficult and involve large uncertainties, since the best variety of the pure cellulose available viz, that from cotton or flax consists of fibres of external diameters seldom exceeding 0 02 of a mm and even at that the fibres are hollow, thereby making the estimation of the stress a matter of great uncertainty Any transverse stress on the fibre is likely to produce a deformation of the hollow space rather than the cellulose material unless the fibre can be split open and laid flat It is, however, not a very difficult matter to make a computation of the transverse modulus from structural considerations following the method adopted by Meyer and Lotmar in their theoretical computation of the axial modulus

According to X-ray evidence, cellulose fibres are built up of crystallites of cellulose arranged parallel to each other, each crystallite of cellulose containing a number of cellulose chain molecules arranged parallel to each other as shown in the diagram, fig 15 The ring in the glucose residue is sensibly plane except for the oxygen atom in the ring which is outside the plane The hydrogen atoms and the hydroxyl groups are also sticking out at definite angles to the plane From X-ray evidence it is known that the distance between two such parallel chains in a direction perpendicular to the plane of the ring is about 3 9Å, so that the distance between the (OH)'s at 1 and 2 from those at 1′ and 2′ will be of the right order of magnitude for a hydroxyl bond[68], i e, about 2 7 to 2 9Å between the two centres Also the distance between the atoms and groups at 3 and 4 from those at 3′ and 4′ will be favourable for a hydrogen bond between 3 and 3′ and another between 4 and 4′ There will be similar bonds in a direction parallel to the plane of the ring

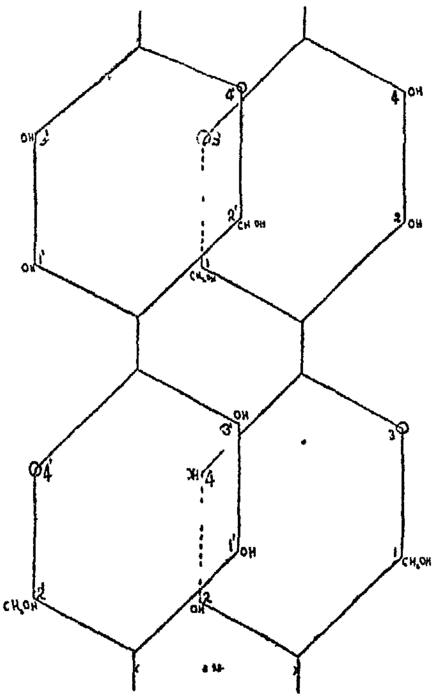


FIG 15

between neighbouring chains, but it is evident that considering in general, a glucose residue will contribute two hydrogen bonds and two hydroxyl bonds between adjacent chains Since a hydroxyl bond strength is not very different from a hydrogen bond strength[69], one might consider the transverse binding force between two adjacent cellulose chains per glucose residue as equivalent to that of four hydrogen bonds Besides this, there will, of course, be the Van der Waal forces between the atoms in the two chains, since the distance of 3 9Å between adjacent chains is smaller than the usually accepted range of Van der Waal forces, which is of the order of about 4 to 6Å It is evident therefore that the cellulose chains are transversely linked to one anothei by secondaiy bonds both of the dipole and the Va Waal types and in a computation of the tiansveise modulus ot city of cellulose, these secondaiy bonds should be consideied as ; iise to the elastic modulus

In computing the axial modulus of cellulose, Meyer and L have assumed in their computations that, foi each glucose iesi cellulose, theie aie eight lineai bonds and eight angular bonds they assume that an angulai deformation is 20% as strong as a deformation so that in teims of lineai bonds the total binding along the axial diiection pei glucose residue will coiiespo $(8+\frac{8}{5})=9\ 6$ lineai bonds In a similai manner, in the tian diiection, assuming both lineai and angular detormations of the gen and hydioxyl bonds likely, the equivalent number of hyc bonds per glucose iesidue will be equal to $4+\frac{4}{5}=4\ 8$

The binding foices of hydiogen and hydioxyl bonds aie i calculated most easily from obseivations on the Raman speci compounds of like structuie with and without hydrogen bonds culations made by various obseiveis, though not agreeing rigou all indicate that a hydrogen bond is veiy much weakei than a pi valence bond It will be a faii mean ot all the likely values fo the liteiatuie on the subject to assume that a hydrogen bond is one tenth as strong as a piimaiy valence bond Theiefoie the verse binding foice between two neighbouiing glucose iesidu be of the oidei of 4 8/10 oi 48 of a piimaiy valence bond

Theie is still anothei factor which should be taken into a in a consideiation of the anisotiopy of cellulose The iing struc the cellulose molecule will contiibute a certain iesistanc tiansveise stiess and so its effect should be consideied with that due to the secondaiy bonds When a tiansveise is applied to a cellulose fibre, its effect will be to pro laige stiain in the hydiogen bond length and a smallei stiain iing structure, just as a force applied along two spiings coi up in series will pioduce a longer extension in the weakei than in the strongei spring The actual extension in any will of course be equal to the product of the strain in that spring into its length Considering the hydrogen bonds between neighbouring cellulose chains as a weak spring connected in series to a stronger spring represented by the valence bonds in the ring in cellulose, it is evident that, in order to obtain the effect of a transverse stress on cellulose, it is necessary to get an idea of the relative strengths of the secondary binding between the chains and the primary valence binding inside the ring, as well as the relative dimensions of the hydrogen bond length and the valence bond lengths in the rings

In order to obtain the latter quantity viz, the relative dimensions of the hydrogen bond length to the valence bond length, it will be necessary to find out the distance between the axes of adjacent cellulose chains in a cellulose structure The actual length of a hydrogen bond is known to be about 2 55Å so that the difference between the distance between the axes of adjacent cellulose chains and 2 55Å will be the length corresponding to the valence bonds in the ring The actual spacial model of cellulose is as shown in the diagram, fig 16, consisting of four cellobiose units per unit cell and if we imagine such a unit cell to repeat itself indefinitely in three dimensions, we shall obtain the actual cellulose structure in which each cellulose chain will be surrounded uniformly by four others, at the corners of a square, itself being at the centre as shown in the figure

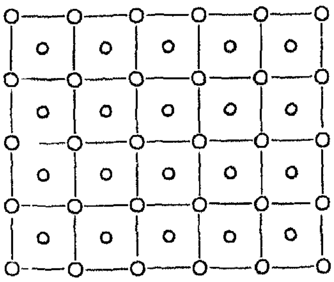


FIG 16

Taking one such square and remembering that the cross-sectional dimensions of a unit cell, according to X-ray evidence, are 8 35Å × 7 9Å, the distance between the axes of any two cellulose chains will come out as 5 8Å

The relative strengths of the hydrogen bonding between adjacent chains and the valence bonding in the rings can be obtained in the following manner It has already been shown that the four hydrogen bonds between adjacent cellulose chains will be equivalent to 0·48 of a primary valence bond. Considering the binding forces in a ring, it is obvious that a transverse stress can produce no strain in the four valence bonds that are parallel to the chain-axis. Hence the four other valence bonds which are inclined to the chain-axis will be the only effective bonds in opposing the transverse stress. Also the the deformation of the eight valence angles will contribute to the lateral strain and hence should be considered as opposing a transverse strain. Hence the total resistance to a transverse stress in a ring will be equivalent to four primary bonds and eight angular bonds. Assuming an angular bond to be 20% as strong as a primary bond, the total lateral strength of a ring will be equivalent to $4+\frac{8}{5}=\frac{28}{5}$ primary bonds. Hence the relative strengths of the ring and the hydrogen bonds will be in the ratio of $\frac{28}{5}$: 0·48 or very nearly in the ratio of 12 : 1. The corresponding strains in the hydrogen bond lengths and the ring-structure, will be in the ratio of 12 : 1. The relative dimensions of a hydrogen bond length and a ring-structure being in the ratio of 2·5Å to (5·8 − 2·5) or 3·3Å, any strain e in the hydrogen bond length will produce a total transverse extension equal to $(2{\cdot}5e+\frac{3{\cdot}3}{12}e)$ i.e., $2{\cdot}77e$. The overall distance between adjacent chains in the transverse direction being 5·8Å, the overall strain will be $\frac{2{\cdot}77}{5{\cdot}8}e$. Thus the effect of ring-structure on the hydrogen bonds is effectively to reduce the strain in the ratio of 1 : 2·1. This could be regarded as an apparent increase in the transverse bond strength of the hydrogen bonds in the ratio of 2·1 : 1. Hence taking into account the effect of the deformation of the ring also by a transverse stress, the transverse strength of cellulose will be equivalent to $2{\cdot}1\times 0{\cdot}48=1{\cdot}01$ primary valence bonds. The strength of the cellulose chain along the chain-axis being equivalent to 9·6 primary bonds, the elastic anisotropy of the cellulose molecule will be as 9·6 : 1·01 or very nearly as 9·5 : 1·0.

The Young's modulus of cellulose in any cellulose structure will depend upon the degree of orientation of the cellulose molecules. Ramie cellulose possesses a high degree of orientation of molecules while the cellulose in wood as revealed by the X-rays is not quite so well orientated The most probable value of the Young's Modulus of cellulose in wood along the axial direction would appear to be about 80% of its value in ramie In the case of 'Bombax Malabaricum', the X-ray study reveals an orientation of cellulose which is at best only half as good as that in the other woods so that the axial Young's Modulus of cellulose in this wood should be taken to be only half that in the other woods Accordingly, taking the value of Young's Modulus of ramie as $5 0 \times 10''$ dynes/cm ^{2} as measured experimentally by Meyer and Lotmar, the value of the longitudinal modulus of cellulose in the hard woods can be taken as $4 0 \times 10^{11}$ dynes/cm ^{2} while that in 'Bombax Malabaricum' will be taken as $2 0 \times 10^{11}$ dynes/cm ^{2} Applying the anisotropy ratio of 9 5 1 as between the axial and transverse directions, the transverse Young's Modulus of hard woods will come out as $0 42 \times 10^{11}$ dynes/cm ^{2} while in 'Bombax Malabaricum' its value will be $0 21 \times 10^{11}$ dynes/cm ^{2}

2 LIGNIN AND ITS PROPERTIES

The next important major constituent of wood after cellulose is the incrusting substance of the cell-wall viz, lignin Usually it forms about 25 to 35% by weight of wood material Unfortunately, however, the amount of exact knowledge on the chemical or physical properties of lignin is very little though a large amount of analytical work has been done on lignin to elucidate its chemical constitution It is a compound of carbon, hydrogen and oxygen with more than 30 carbon atoms in the empirical molecule and the number of hydrogen atoms in the molecule are too many disproportionately in excess of the oxygen atoms to entitle the substance to be classified as a carbohydrate The actual molecule is supposed to be a high molecular polymer with a molecular weight in the neighbourhood of 6000 So far as its chemical structure is concerned, there is uncertainty even about the nature of its nuclei, whether they are aromatic or hydro-aromatic or other complex type of ring-structure By several reactions with alkalies, concentrated acids and halogens the presence of hydroxyl, methoxyl, methylene and aldehydic or ketonic groups has been definitely established

Ritter has made a detailed study of the lignin content of wood and has come to the general conclusion that Spring wood contains more lignin than Summer wood The more interesting contribution of Ritter to our knowledge of lignin in wood, specially for purposes of the present study, is with regard to its distribution in wood According to Ritter[71] the lignin in wood is of two kinds one forming part of the cell-wall whose nature is amorphous and which falls to powder during the hydrolysis of the cell-wall by 72% sulphuric acid The other kind of lignin is structural and is almost exclusively the main constituent of the middle lamella in wood This middle lamella lignin possesses a honeycomb-like structure, constituting a sort of open frame-work which is interpenetrated by the fibres He estimates that about 25% of the total lignin is in the cell-wall while the rest makes up the middle lamella As a result of a large amount of work on cellulose and lignin Freudenberg[72] has elucidated the relation of cellulose to lignin in wood According to him the lignin in wood, whether in the cell-wall or the middle lamella, is entirely amorphous He considers the lignin in the middle lamella to be permeated with hemicellulose and to form with the hemicellulose a homogeneous structure which encloses the whole cellulose net-work Freudenberg is definitely of opinion that the bulk of the cellulose in wood has no contact with lignin though he admits that it is just possible that the lignin might work its way into the outer layers of the fibres The lignin in wood is supposed to play the same part as what the concrete in reinforced concrete does

The amount of information available in the literature on the physical properties of lignin is almost next to nothing Since, however, for a proper understanding of the effect of lignin on cellulose in wood, it would be necessary to know something of the physical properties of lignin, it was decided to study those necessary properties of lignin For this purpose lignin was obtained by precipitation from the lye solutions obtained during the pulping of wood in the paper industry and another sample of very pure lignin was made available to the author by the kindness of Mr Mani of the General Chemistry Dept of the Indian Institute of Science, lore This lignin had been prepared from wood by an electrolytical process developed by Mr Mani and its purity had been and established by various tests Both varieties of lignin employed in the study and gave comparable values The lignin mixed up with a small quantity of water to form a thick plastic and the paste was pressed into the form of a disc of three diameter and about an eighth of an inch in thickness in a hydraulic press under a pressure of nearly 500 lbs per sq For purpose of elastic measurement and measurement of il expansion, the paste was pressed into the form of a rod of about ches length and about a quarter of an inch in diameter under a pressure in a special die Some difficulty was experienced at ecause, though good specimens were produced by the pressing ulds, it was found that the specimens cracked and crumbled wder on drying This difficulty was got over by leaving the iens inside the moulds with the pressure still on till they were lry The shape was then retained permanently

The density of lignin was measured with a piece of the ed rod as well as with the powder making use of a density and kerosene The close agreement between the density of wder and of the moulded rod is evidence of a compact structure been produced in the moulding operation

The Young's modulus was measured by employing the rod of in a single cantilever arrangement with an optical lever to re the deflection The thermal conductivity was measured at nt temperatures with a Lee's disc apparatus according to the l described in the section on the thermal conductivity of wood iermal expansion was measured by arranging the rod of lignin an electric heater specially made for this purpose and capable ng maintained at different temperatures up to 200 C and pansion was measured by an optical lever arrangement de- t which are given in the section on the thermal expansion od The results of the various measurements are given below

y of powder . = 1 645 gms / c c

y of the piece of rod. — 1·62 gms / c c

Range of temperature ..	33–100°C	100–142°C	142–203°C
Coeff of Thermal Expansion	$2\ 056 \times 10^{-6}$	$2\ 267 \times 10^{-6}$	$2\ 315 \times 10^{-6}$
Range of temperature .	64° 6C	100° 5C	145°.5C
Coeff of Thermal Conductivity (in cal gm sec units)	·000190	000206	000181
Young's Modulus ..	=	$0\ 20 \times 10^{11}$ dynes/cm²	

CONCLUSION

The density of lignin is almost the same as the density of cellulose which is given to be something between 1 58 and 1·63 The fact that, while both the major constituents of wood amounting to more than 80% of it possess a density as high as 1 5, wood itself possesses a density which hardly approaches 1 0 while it usually lies far below it, is certainly due to the hollow structure of the wood fibres The Young's Modulus of lignin is remarkably low compared to that of cellulose but is of the same order of magnitude as that of similar cementing organic materials like proteins, conchyolin etc The co-efficient of thermal expansion shows a slow increase with temperature in conformity with the amorphous nature of the material Its absolute value at any temperature is quite small being less than that of glass and similar amorphous substances Its thermal conductivity is very poor as might have been expected from its being an important constituent of wood The variation of thermal conductivity is however irregular and quite small It at first slightly increases with temperature as might be expected of an amorphous substance but after about 120° it begins to decrease again Neither the increase in the early stages nor the subsequent decrease is of any great magnitude

V CHAPTER—INTERPRETATION OF RESULTS

In the present chapter an attempt is made to understand the experimentally obtained results recorded in the second chapter in the light of the structure and constitution of timber and the properties of its major constituents recorded in the two subsequent chapters A ission based upon the combined effect of cellulose and lignin will airly representative of the behaviour of wood since in most cases two constituents make up nearly 90% of wood material her it is only these two components that possess a definite nuity of structure with specific well-defined properties All the components in wood amounting to about 10% of its bulk are phous materials of very ill-defined properties and their effect will ute a negligible factor

1 The Elastic Properties of Wood

A proper estimate of the elastic properties of wood should take account all the components of wood However, the three major ituents, viz, cellulose, lignin and hemi-celluloses make up nearly of wood and will therefore be the chief-factors deciding the ic nature of the bulk material Of these three, the role of hemi-loses in influencing the elastic modulus of wood will be a very r one for various reasons The little information we possess t the hemi-celluloses is enough to justify our ignoring its contri-n to the elasticity of timber The hemi-celluloses are a heterogen-mixture of a large variety of poly-saccharide carbohydrates of in phous constitution They possess neither a continuity nor a ture in the framework of wood but remain dispersed in the body ood, mainly in its ligneous portion Indeed, so much of the total celluloses in wood is found dispersed in lignin that a school of nists have advanced the theory that hemicelluloses are the irsor of lignin, which, they say, is formed by the condensation of -celluloses On top of these considerations is the fact that celluloses usually do not represent more than a tenth part of l and being of an amorphous nature with neither form nor shape ood, their contribution to the elastic strength of timber is not to be of any considerable magnitude Hence in the following ission, the elastic modulus of wood is considered in terms of the erties of cellulose and lignin

Of the two important constituents, cellulose will contribute to the elastic behaviour of wood than lignin since it constitutes more than half the bulk of wood and in addition possesses a much larger elastic modulus than lignin with a pronounced anisotropy of elasticity The effect of lignin will be to modify the properties of cellulose since usually the amount of lignin is half or more than half that of cellulose and besides, lignin in wood possesses a continuous structure closely adhering to the cellulose frame work and completely surrounding it It is in fact acting like the cementing material, conchyolin, in the case of molluscan shells studied earlier in this investigation

The cellulose in wood occurs in the form of hollow fibres and hence the gross structure of cellulose will itself introduce an anisotropy of elasticity in wood quite apart from the inherent anisotropy of cellulose Thus the total anisotropy of wood will be made up of two parts, one, the structural anisotropy due to the gross structure of the cellulose fibres and two, the intrinsic anisotropy of the cellulose molecule itself. Hence a complete estimate of the elasticity of wood will have to be made in two stages (1) the stage in which the effect of the gross structure of the fibres on the inherent anisotropy of cellulose is considered and (2) the stage in which the effect of the enveloping lignin on the total anisotropy of wood is considered

1 *Gross structure*

(a) *Comparison of different varieties of timber*—From the remarkable parallelism between the Young's Modulus and density in the various woods, one is almost tempted to conclude immediately that the elasticity of wood is a direct function of its density Of course, also, it stands to reason that for a given dimension, the greater the number of resisting units, the greater will be the force and energy necessary to produce a given elastic deformation and consequently the greater will be the elastic modulus This conclusion holds fairly accurately for specimens taken from different directions of the same species of wood but directly a comparison between specimens of different kinds of wood is made, it is found that the relation breaks down Thus in the radial longitudinal section, the Young's Modulus of 'Tectona Grandis' is twice as large as that of 'Terminalia Tomentosa' while in the same direction in the same section, the density of the former is only about 85% that of the latter In the tangential longitudinal section, 'Terminalia Paniculata' has got a density more than 30% greater than 'Tectona Grandis' but the Young's Modulus of the former is slightly less than that of the latter It is, therefore, evident that apart from the amount of wood substance present, the way in which the material is distributed in the timber is of great importance in deciding the elastic properties of wood With a density half that of 'Terminalia Tomentosa', 'Bombax Malabaricum' maintains an elastic modulus quite comparable to and sometimes even greater than that of the former 'Bombax Malabaricum' has evidently achieved this by making a liberal use of the fact that for the same amount of material, a hollow structure has a greater elastic resistance than a solid structure The thickness of fibre wall relative to fibre diameter is smaller in 'Bombax Malabaricum' than in 'Terminalia Tomentosa' Further reinforcement has been secured by the development of cross membranes in 'Bombax Malabaricum' within the fibre unit Clark[73] experimenting on the wood of the English ash, 'Fraximus Excelsior' finds that specimens of the same specific gravity and similar anatomical structure differ by as much as 30% in strength and comes to the conclusion therefrom that probably the chemical and physical properties of cellulose are responsible for this It is more likely that an explanation of Clark's observations is to be sought for in the difference in orientation of the micelles or crystallites of cellulose within the fibre of the different specimens This difference in crystallite orientation within the fibre will not make any difference in the anatomical structure as revealed by the microscope nor even in the specific gravity It will be revealed only by an X-ray investigation Such differences in micellar orientation of the same species can be conceivably brought about by the different rates of growth A slow growth, induced by lack of seasonal rains or cutting away of the foliage during the growing season of the year, is favourable for better micellar orientation since the production of new cells will be slower and the stretching of already existing cells will take place to a greater extent A slow growth will thus produce a timber mechanically stronger than a quick growth

(b) *Comparison of different sections of the same species*—The next important fact that comes of an examination of the results is the variation of the relative elasticity between the tangential and radial sections as we pass from one species to another Thus in 'Tectona Grandis' and 'Bombax Malabaricum', the radial section is more elastic than the tangential section while in 'Terminalia Paniculata' and 'Artocarpus Hirsuta', the two sections have almost the same elasticity In 'Terminalia Tomentosa' and 'Dalbergia Latifolia' the tangential section is more elastic than the radial section A study of the longitudinal section as shown by photo-micrographs suggests that the properties in a longitudinal direction are strongly influenced by the nature and distribution of the medullary rays It is well-known that rays are mechanically very much weaker than fibres and obviously an abundance of rays in large patches should detract considerably from the mechanical strength The tangential longitudinal sections of 'Tectona Grandis' and 'Bombax Malabaricum' show that the fibres are running almost straight and the rays are occurring in large patches and in great abundance Evidently, therefore, there is a comparative scarcity of fibres in the tangential plane as against the radial plane with the corresponding lower value of the modulus in the tangential than in the radial plane In 'Terminalia Paniculata' and 'Artocarpus Hirsuta' the fibres are long and straight and the rays are small, irregular and scanty with the result that the radial and tangential planes are about equally strong In 'Terminalia Tomentosa' and 'Dalbergia Latifolia', on the other hand, the rays are small, numerous and uniformly distributed The fibres are wavy and strongly interlocked in the latter case The wavy nature of the fibres in the tangential plane prevents, as it were, the rays from being subjected to direct stress while it is obvious that a radial section will cut through a number of fibres and expose the rays to direct stress Accordingly the tangential sections are mechanically stronger than the radial sections

(c) *Comparison of different directions of the same section*—Coming to a still more detailed examination of the properties within the same section, we find here that we have the most important characteristic of the mechanical properties of wood Whether we consider the tangential or the radial section, the modulus along the fibre axis is many times that across it This ratio varies for the same section from species to species and for the same species, it varies as between the tangential and radial sections Its value depends upon the thickness of the fibre wall in relation to fibre diameter, increasing with diminishing thickness of wall and vice versa Thus in 'Dalbergia Latifolia' with very thick walls the ratio is about 7 1 while in the thin walled 'Bombax Malabaricum' the ratio is about 20 1

(d) *Theoretical computation of the Young's modulus of a cellulose fibre*—The ratio of the Young's Modulus of wood in the longitudinal direction to that in the transverse direction can be calculated theoretically from the known elastic properties of cellulose in the two directions together with the known microscopic structure of the cellulose fibres in wood The calculations, of course, involve certain approximations which are inevitable in a problem of this kind The most important of these approximations is the consideration of the cellulose fibre as a cylindrical tube of internal radius 'a' and external radius 'b' In the actual experimental determination of the Young's Modulus no account is taken of this hollow structure, with the result that any applied force being supposed to be uniformly distributed over the entire cross-section will give rise to a smaller value of the stress-distribution than what actually obtains in the specimen and the modulus calculated on this ignoring of the hollow structure will be less than the real value of the modulus The change of dimensions of hollow tubes will give rise to different strains along the axial and radial directions even though the stresses in the different directions have the same value and consequently the apparent elastic modulus of a hollow structure along and across the axis of the figure will have different values even though the material in the solid state should be elastically isotropic and in the case of an intrinsically anisotropic substance like cellulose, the anisotropy will be enhanced by the hollow structure The following method enables us to compute the Young's Modulus of a hollow structure along the axial and radial directions in terms of the Young's Modulus of the material in the corresponding directions

(i) *Longitudinal*—Let us consider a hollow tube of internal radius 'a' and external radius 'b' subjected to an axial stress F. In the absence of the knowledge of the hollow structure, the apparent cross-section of the tube will be taken as πb^2. The axial stress F will be the effect of a force $\pi b^2 F$ acting along the axis. The real value of the cross-section being $\pi(b^2-a^2)$, the effective stress will be the ratio of the force to cross-section.

$$\text{The effective stress} = \frac{\pi F b^2}{\pi(b^2-a^2)} = \frac{Fb^2}{b^2-a^2}$$

If the axial Young's Modulus of cellulose is q,

$$\text{strain along the axis} = \frac{\text{stress}}{\text{modulus}} = \frac{Fb^2}{q(b^2-a^2)}$$

This will be the real strain observed in the experiment but the stress supposed to be producing this strain will be F. Therefore, the apparent value q_1 of the modulus will be the ratio of the apparent stress to the observed strain.

$$q_1 = \frac{F}{Fb^2/q(b^2-a^2)} = \left[\frac{b^2-a^2}{b^2}\right] \times q$$

(If the cross-section of the tube be square instead of circular, with internal and external sides of length 'a' and 'b' respectively, the actual cross-section will be greater in the ratio of 1 $\frac{\pi}{4}$ but their ratio will be unaffected so that still $q_1 = \left[\frac{b^2-a^2}{b^2}\right] \times q$)

(ii) *Transverse modulus*—The radial strain of a hollow tube under radial stress gives rise to certain complex effects caused by lateral contractions in the radial section at right angles to the stress and hence Poisson's ratio will be involved in the mechanics of the problem.

The radial displacement 'u' at a distance 'r' from the axis of a hollow cylindrical tube of internal and external radii 'a' and 'b' respectively under steady uniform pressure P_a on the side of radius 'a' is given by[74]

$$u = \frac{a^2 P_a}{(b^2-a^2)q'}\left[(1-\sigma)r + (1+\sigma)\frac{b^2}{r}\right]$$ where σ is the Poisson's

ratio of the material and q' the transverse Young's Modulus of cellulose

In the case of a hollow fibre of cellulose any stress applied radially on the outside will produce a radial inward displacement of any point in the cross-section and it is very unlikely that there will be any stress on the inner surface since the fibre is hollow containing only air In such a case, calling P_b the stress on the surface of radius 'b' and consequently interchanging 'a' and 'b' in the expression for 'u' we obtain the displacement 'u' at a distance 'r' from the axis as,

$$u = \frac{b^2 P_b}{(a^2 - b^2)q'}\left[(1-\sigma)r + (1+\sigma)\frac{a^2}{r}\right]$$

When $r = b$, i e , at the outer edge of the fibre,

$$u = \frac{b^2 P_b}{(a^2 - b^2)q'}\left[(1-\sigma)b + (1+\sigma)\frac{a^2}{b}\right]$$

$$= \frac{b P_b}{(a^2 - b^2)q'}\left[(1-\sigma)b^2 + (1+\sigma)a^2\right]$$

The strain at the outer surface along the radius is equal to

$$\frac{u}{b} = \frac{P_b}{(a^2 - b^2)q'}\left[(1-\sigma)b^2 + (1+\sigma)a^2\right]$$

The apparent modulus q_2 in the radial direction will be equal to $\frac{\text{stress}}{\text{strain}} = \frac{P^b}{u/b}$

$$q_2 = \frac{(a^2 - b^2)q'}{(1-\sigma)b^2 + (1+\sigma)a^2}$$

$$\text{or } \frac{q_2}{q'} = \frac{a^2 - b^2}{(1-\sigma)b^2 + (1+\sigma)a^2}$$

In the above derivation we have assumed the cellulose fibre to be long and open at the ends It however, we treat it as a tube closed at both ends, the result will be slightly different By the application of the generalised Hooke's law to a small approximately rectangular element of the wall with radial sides, in the case of a tube of radius 'r' closed by hemispherical or semi-ellipsoidal ends with a small thickness e of wall, e being small compared to 'r' and subjected to a stress P, the change, u, in radius is given by[75]

$$u = \frac{2-\sigma}{q'} \frac{Pr^2}{2e}$$

$$\text{Radial strain} = \frac{u}{r} = \frac{2-\sigma}{q'} \frac{Pr}{2e}$$

$$\text{Modulus } q_2 = \frac{\text{stress}}{\text{strain}} = \frac{P}{u/r} = \frac{2e\,q'}{(2-\sigma)r}$$

$$\frac{q_2}{q'} = \frac{2e}{(2-\sigma)r} \qquad \cdot \qquad \text{II}$$

Thus the Young's modulus of a hollow cellulose fibre can be theoretically calculated and the following table sets forth the calculated values of the Young's modulus in terms of the Young's modulus of cellulose in the corresponding directions for different ratios of wall thickness to fibre diameter In the case of the transverse modulus, the values have been obtained by using both the equations I and II and are entered in columns 4 and 5 of the table

TABLE XXXIV

No	Ratio of Wall-thickness to Fibre diameter	Young's Modulus along Fibre	Young's Modulus across Fibre	
			Equation I	Equation II
1	1 4	0·75 q	0·51 q'	0 59 q'
2	1 5	0·64 q	0 41 q'	0·47 q'
3	1 6	0 55 q	0·32 q'	0·40 q'
4	1 7	0·50 q	0 30 q'	0·34 q'

2 THE EFFECT OF LIGNIN ON THE GROSS-STRUCTURE OF CELLULOSE FIBRES

For a proper estimate of the effect of lignin on the elasticity of ulose fibres, it would be necessary to have an idea of the mode of ribution of lignin in wood In this connection the work of Ritter Freudenberg is of great importance According to Ritter, the in in wood is present in two forms, one form existing as a disperse se distributed in the cell wall in a perfectly structureless amor- ous state while the other part forms a continuous structure consti- ng the middle lamella in wood Ritter however does not say thing as to whether the latter lignin is also amorphous intrinsically udenberg while giving conclusions generally agreeing with Ritter, mitely finds the middle lamella lignin to be entirely amorphous and t the lignin dispersed in the cell wall is confined to the primary, ondary and perhaps also to the tertiary layers of the cell wall but t most of the cellulose crystallites in the cell wall have no contact h lignin Remembering that the lignin content in most woods is in whereabouts of 30%, it will be a fair estimate to assume that 25% the total weight of wood is present as lignin in the middle lamella would thus come out that in most woods, the amount of lignin, closing the cellulose is very nearly half the weight of the enclosed lulose (25% 50%) Since the density of cellulose is nearly the ne as that of lignin the proportion by volume of lignin to cellulose most woods will be as 1 2 (In the case of Bombax Malabaricum ratio will be as 1 10)

Longitudinal Elasticity—The longitudinal elasticity of a lulose fibre sheathed in lignin (lignified cellulose fibre) as it occurs wood can be estimated as follows Taking any length of a lignified re, let the area of cross-section of the cellulose portion be a and of lignin portion be β Any extension longitudinally of the fibre will oduce equal extensions in the cellulose as well as the lignin portions t the stress distribution in the two portions will be different If we ume the longitudinal elastic modulus of cellulose in wood to be q d the elastic modulus of lignin to be q, the stress in the two portions ll be proportional to the elastic moduli Let 'e' be the longitudinal ain of the complete fibre

Then, the stress in the cellulose portion = eq
and the stress in the lignin portion = eq

The force on the respective portions will be equal to the stresses in the portions multiplied by their cross-sectional areas

Hence, force acting on the cellulose portion = $eq\alpha$
and force acting on the lignin portion = $eq\beta$
Total force producing the longitudinal strain = $e(\alpha q+\beta q)$

This force will be applied on the cross-section of the fibre and so the apparent stress will be equal to the ratio of the total force to the total area

$$\text{Apparent resultant stress} = \frac{e(\alpha q+\beta q)}{(\alpha+\beta)}$$

and since the strain is e, the apparent modulus will be equal to the ratio of the resultant stress to the total strain

$$\text{Resultant modulus} = \frac{e(\alpha q+\beta q)}{(\alpha+\beta)e} = \frac{\alpha q+\beta q}{(\alpha+\beta)}$$

In the case where the volume of lignin is half that of cellulose, the cross-section in any given length of fibre being proportional to the volumes will also bear the same ratio to one another Hence in such cases,

• Substituting $4 \times 10''$ dynes/cm.^{2} for q,

$0\ 2 \times 10''$ dynes/cm^2 for q and $\alpha=2\beta$ we obtain the resultant longitudinal elastic modulus of cellulose

$$=q_1=\frac{2\times 4+0\ 2}{3}=\frac{8{\cdot}2}{3}=\boldsymbol{2{\cdot}73\times 10^{11}\ dynes/cm.^2}$$

In the case of Bombax, $q=2\times 10^{11}$ dynes/cm ^{2}, q is the same as before, while

$$q_1=\frac{20{\cdot}2}{11}=1\ 84\times 10^{11}\ \text{dynes/cm}^2$$

Transverse elasticity—The following considerations help to elucidate the transverse elastic modulus of a cellulose fibre sheathed in lignin Any transverse stress applied to a fibre will be communicated equally on the cellulose portion as well as the lignin portion and as such, the strain produced in the transverse direction in the two portions will vary inversely as the elastic modulus in the respective portions The al transverse displacements produced in the two portions will how- depend upon the actual thickness of the portions The thickness of cellulose or the lignin portion will depend on the relative size of the rnal to the external radius of the fibre, since for a given amount naterial a greater diameter of fibre will reduce the thickness of the of material

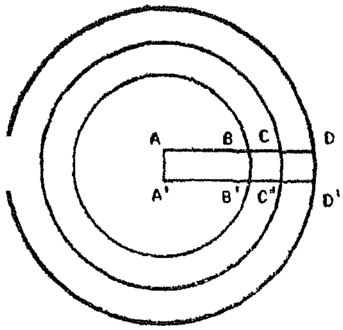


FIG 17

Consider a cross-section of the complete fibre of wood, in which AB($=a$) represents the radius of the hollow portion inside the fibre, AC($=b$) represents the outer radius of the cellulose portion and AD ($=c$) represents the outer radius of the lignin portion

The thickness of the cellulose portion $=(b-a)$
and thickness of the lignin portion $=(c-b)$
Since the volume of cellulose is twice that of lignin,

$$\pi(b^2-a^2)=2\pi(c^2-b^2) \qquad \text{I}$$

Let us consider an average fibre of wood in which the cell l thickness is $\frac{1}{5}$ of the fibre diameter as examined photo-micro- phically on the cellulose fibres under crossed nicols, then $a)=\frac{1}{5}$ (2b)

Hence $b=\frac{5}{3}a$

Substituting this value of b in equation I, we obtain

$c=1\ 9a$ so that $(b-a)=0\ 66a$ and $(c-b)=0\ 24a$

If we now consider a thin strip BDD'B' isolated along the ial direction and subjected to a radial stress S,

Strain in the cellulose portion $BC=\dfrac{S}{q'}$ where q' is the trans- se modulus of cellulose

and strain in the lignin portion $=\dfrac{S}{q}$

∴ Extension in the cellulose portion = Strain × length

$$=\frac{S}{q'} \times BC=\frac{S}{q'}\,(66a)$$

and Extension in the lignin portion $=\frac{S}{q}\ CD=\frac{S}{q}(24a)$

$$\text{Total radial extension}=Sa\left[\frac{66}{q'}+\frac{24}{q}\right]$$

$$\text{Resultant radial stress}=\frac{\text{Extension}}{\text{Length}}=\frac{Sa\left[\frac{66}{q'}+\frac{24}{q}\right]}{66a+24a}$$

$$\text{Resultant modulus}=\frac{\text{Stress}}{\text{Strain}}=\frac{S}{\frac{S}{9}\left[\frac{66}{q'}+\frac{24}{q}\right]}$$

Substituting 0.42×10^{11} dynes/cm^2 for the transverse modulus of cellulose in wood and 0.20×10^{11} dynes/cm for the modulus of lignin, we obtain for the transverse Young's modulus of lignified cellulose fibre the value $q_o = 0.305 \times 10^{11}$ dynes/cm^2.

A similar calculation for fibres in which the wall thickness is 1/4 and 1/7 of the total fibre diameter gives respectively, the values 0.315×10^{11} and 0.295×10^{11} dynes/cm^2 for the modulus.

Corresponding values for 'Bombax Malabaricum' can be calculated by substituting for equation 1, the equation

$$\pi\,(b^2-a^2)=10\pi(c^2-b^2)$$

1. *Combined effect of gross-structure and lignin*.—We are now in a position to calculate the elastic modulus of wood along and across the fibre directions by taking into consideration both the structural anisotropy and lignin to modify the intrinsic anisotropy of cellulose. The following table sets forth the calculated and observed values of the longitudinal and transverse modulus of elasticity of the various timbers obtained by an application of the above method.

TABLE XXXV

No	Name of Timber	Ratio of Wall-thickness to Fibre diameter	Young's Modulus along fibre		Young's Modulus across fibre	
			Calculated	Observed	Calculated	Observed
1	Terminalia Tomentosa	1 6	1 52	1 2	0 15	0 12
2	Terminalia Paniculata	1 5	1 76	1 5	0 13	0 22
3	Artocarpus Hirsuta	1 5	1 76	1 1	0 13	0 10
4	Dalbergia Latifolia	1 4	2 04	1 7	0 19	0 21
5	Tectona Grandis	1 4 1 5	2 04 1 76	1 9	0 19 0 13	0 11
6	Bombax Malabaricum	1 7	0 88	1 1	0 06	0 05

Considering the unavoidable uncertainties and necessar approximations involved in the calculations, the agreement betwee the calculated and observed values should be considered good I general the observed values are slightly smaller than the calculate values due evidently to imperfections of actual structure deviating fron the regularity of an assumed geometric structure The case of th longitudinal modulus of 'Bombax Malabaricum' is exceptional in th sense that the observed value is sensibly greater than the calculate value This is very likely due to the fact that this timber is th only one of the timbers examined which has developed cross members inside a fibre Such a development is conducive to extra strength and apparently the observed value is in excess of th calculated value since in the calculations, no account has bee taken of the effect of these cross-members The reason why th transverse modulus of 'Terminalia Paniculata' is greater than th calculated value is rather obscure The slight excess of the observe transverse modulus over the calculated value in the case of 'Dalbergi Latifolia' is probably due to the effect along the transverse direction of the contribution towards elasticity of the extremely numerous an extraordinarily regularly arranged medullary rays, characteristic c this wood

2 *Thermal Conductivity*—The explanation of the therma conductivity of wood on any theoretical basis will be beset with con siderable difficulty According to modern conception[76], metallic con duction is based upon the zone theory of the valence electrons in th crystal lattice In the case of the non-metals, however, the principa factor involved in the mechanism of thermal properties is the energ states of the nuclear vibrations rather than those of the valence elec trons, although the latter may serve to throw additional light on therma properties[77] When heat is supplied to one part of a material th nuclear vibrations there become stronger and stronger and are pro pagated through the material in the form of what are commonl known as the Debye sound waves Even though these waves trave with the velocity of sound, their mean free-path is small This is du to two main causes In the first place, the waves are scattered o

account of a mutual interference due to the inharmonicity of the elastic forces called into play during their motion and in the second place, a scattering of the wave takes place due to local fluctuations in the structure of the medium. In the case of a crystalline medium where a certain atomic pattern repeats itself very regularly, the structural fluctuations of the medium will be negligibly small and the free-path of the waves will therefore be greater in a crystalline medium than in an amorphous one. This increased value of the free-path of the waves will give an increased thermal conductivity in the material. Thus a substance in the crystalline state will conduct heat much better than the same substance in the amorphous state. A remarkable example of this behaviour is shown by quartz[78]. In the vitreous state the thermal conductivity of quartz is $11.2 \times 10^{-[illegible]}$ while that of crystal quartz is $134 \times 10^{-[illegible]}$. Thus the process of crystallisation has increased the conductivity nearly ten-fold. This conception is also borne out by the fact that the thermal conductivity of crystalline substances diminishes with increase of temperature. Evidently with increase of temperature the increased thermal agitation of the atoms will seriously affect the regularity of the lattice with a corresponding decrease in the free-path of the Debye waves.

Independant optical evidence for the propagation of these Debye waves in solids has been obtained by Raman and Venkateswaran[79] from observations on the light scattering in crystalline and amorphous substances. In the case of crystalline media, positive evidence has been obtained for the presence of the Debye waves and their propagation with the velocity of sound, while very careful observations with amorphous substances have not yielded any similar results.

It is therefore reasonable to expect that a well-ordered structure as that in a crystal will conduce to a better thermal conductivity. Generally in the case of organic compounds it is found that crystallisation increases conductivity considerably though to a smaller degree than in inorganic compounds. Thus β-Naphthalene salicylate[80] in going from the amorphous to the crystalline state conducts heat twice as well.

Furthei, it is reasonable to expect that in a stiucture different binding stiengths in diffeient directions, the thermal ductivity will show a coiresponding anisotiopy being gicatei alon direction of strongei binding It is known that in the ca. giaphite,[81] the conductivity in the plane of the layers is foui tir great as that acros the layeis In asbestos, the conductivity alor fibies is twice what it is across the fibies In the case of wood known that the binding forces in the direction of the fibres is stronger than in the transverse direction and consequently the the conductivity should also show a marked anisotiopy, being great the longitudinal diiection than in the transverse direction Inde would appeai from the expeiimental iesults that the actual aniso is less than what could be expected theoretically The low val the anisotropy of thermal conductivity obseived in the experimen piobably be understood from the following considerations. mechanism of theimal conductivity is a complex one invol as it does, for any one direction, the behaviour of three sets of D waves, one longitudinal and the two otheis transverse The long nal waves will involve the Young's Modulus of the material ir corresponding direction while the transverse waves will involve th torsional moduli in the two mutually perpendiculai directions i transverse plane Thus the anisotropy of thermal conductivity not stand in any simple relation to that of Young's Modulus bu be considerably modified by the torsional moduli of the mateiia which, however, we have no knowledge at present

Perhaps the moie important factor which contributes to low value of the anisotiopy of conductivity in wood is the comb effect of the stiucture of the fibres and the propeities of the li enclosing them As is well-known, the fibres in wood are hc tubes of cellulose enclosed in a lignin sheath Considering average fibre in which the cell wall thickness is one-fifth of the diametei, as already shown in the section on elasticity (refer p 295), the relative areas of cross-section of the hollow space, cellulose portion and the lignin portion will be as 9 16 8, so that hollow space and the lignin together make up moie than the cellu tion of the cross-section In the longitudinal transmission of heat contribution due to the hollow portion will be quite negligible, e the conductivity of the air present in this space is very low e lignin portion can ofcourse conduct some heat but its conducty is very small Consequently, the effective conduction of heat ng the longitudinal direction will be reduced to nearly half its ue in cellulose due to the combined effect of the hollow space and lignin sheath

In a transverse direction, however, the effective conductivity ellulose will not be affected very much The natural conductivity cellulose normal to the chain-axis will itself be low on account of weak secondary bonds in this direction Also, the hollow space n if it could not conduct heat to any appreciable extent, will open the possibility of heat radiation across the empty space from one l of the fibre to the opposite one and to this may be added also contribution to heat transfer by convection in the intervening ce The radiation and convection added on to the small conducty of the air in the hollow space may together make up the heat nsfer across this space comparable to the conductivity of lignin and quite possibly to the transverse conductivity of cellulose

Thus the resultant effect of structure and lignin on the ductivity of cellulose in wood will be to considerably diminish longitudinal conductivity while leaving the transverse one practiy unaffected, so that the anisotropy of conductivity will be sibly reduced

Theory apart, an examination of the experimental results ngs out certain facts prominently As a general rule, the conductiincreases with density The conductivity along the fibre of rminalia Tomentosa' is nearly twice that of 'Bombax Malabaricum l a comparison of the densities of the two woods shows that the nsity ratio is also two Where there is a deviation from this neral rule, photomicrography of the section appears to offer an planation Thus we find that the conductivity of 'Terminalia nentosa' is only 6.2×10^{-4} while 'Tectona Grandis' with a distinctly smaller density has a conductivity of 7.4×10^{-4}. The fibres of the former wood are distinctly wavy in character frequently interposed by numerous patches of medullary rays. The medullary rays are usually very much lighter tissues with large hollow spaces and would contribute very little to conductivity especially in a direction at right angles to their length. 'Tectona Grandis' on the other hand has almost quite straight fibres running parallel in big patches. Thus what is lost in density is more than counter-balanced by a well-ordered structure.

Even more remarkable than this variation with density is the variation of thermal conductivity with direction in wood. The conductivity in the direction of the fibre is a maximum while as a general rule the conductivity across a tangential section is about two-thirds of it and that across a radial section is only about half of it. If it is remembered that while flowing across a tangential section the heat is being transported across the fibres but along the rays while in flowing across a radial section it is being transported across both the rays and the fibres, it is easy to see that the latter conductivity should be smaller than the former. The exception in the case of 'Dalbergia Latifolia' in which the conductivity across the radial plane is greater than that across the tangential plane is apparently due to the fact that the fibres are strongly interlocked and twisted, so that a fibre, instead of running every where longitudinally, will frequently be cutting into the transverse direction with its length now across a radial plane and now across a tangential plane. The higher conductivity along the fibre will therefore contribute to the transverse conductivity and if the shape of the twisted fibre is a helix, as is well-known, with an elliptic section whose major axis is normal to the radial plane, the conductivity across the radial plane will be greater. Further it is seen from the photomicrographs that the rays are not at all straight but are very much distorted on account of the large twisting and interlocking of the fibres with the result that the transport of heat along the rays which will contribute to the conductivity across a tangential plane is very much impeded. It is very significant that in 'Bombax Malabaricum' in ch no real fibre formation is evident and in which mechanical ies are thin-walled and provided with a large number of cross-nbers, the conductivity is fairly the same in all directions Even iis case, the little difference there is between the radial and the ,ential directions is in conformity with the general behaviour of -twisted fibres The very low thermal conductivity of this last ies combined with the fact that it is very light, available in really r large sizes and is, unlike the more costly cork, capable of ig easily worked by hand or on the lathe at very high ds opens up a large possibility for this wood in thermal insulation istries

While there is no much uncertainty and vagueness about the ial mechanism of thermal conductivity in wood it is hardly possible expect that the temperature variation of conductivity could be lained on any simple grounds The results in general, almost ititatively, confirm the observations of Barratt about the increase onductivity of wood with rise of temperature This however has i observed to be the case only with respect to the axial conductivity e the transverse conductivity diminishes usually with rise of tem-iture up to a point and then begins to increase Taking the results ongitudinal conductivity in conjunction with Eucken's observations he variation of conductivity of non-metallic crystalline and amor-is substances, one is likely to conclude that wood in bulk behaves an amorphous substance , but then it will be hard to reconcile this clusion with diminution of conductivity with increasing temperature, east up to a limit, in the transverse direction The very marked otropy of elasticity and thermal expansion will be still more difficult econcile with this idea Evidently it is not quite so simple a matter lraw such hard and fast conclusions on the nature of matter, ecially of such complex material as wood, merely from the behaviour one single property like thermal conductivity Indeed, as has ady been pointed out, the phenomenon of thermal conductivity is ditioned by so many other factors, of which we have at present so e information, that it will be hazardous to venture upon any general clusions at this stage

3 *Thermal expansion*—In the following discussion, in order to avoid the frequent repetition of a qualifying clause, 'a_1' is chosen to represent the coefficient of linear expansion along the fibre, 'a_2' that across the fibre in a tangential plane i e, the tangential transverse coefficient of linear expansion and 'a_3' that across the fibre in a radial plane i e, the radial transverse coefficient

An examination of the results given out in Tables 28 to 34 brings out certain salient points and it will be well to consider these points before attempting a theoretical explanation of them

(1) In general, it is found that the coefficient of thermal expansion runs inversely with the Young's Modulus in any direction Thus the longitudinal expansion is several times smaller than the transverse one and it is already known that the longitudinal elasticity is several times larger than the transverse one If, however, we find out the exact ratio of the transverse coefficient of expansion to the longitudinal one and also the ratio of the longitudinal Young's Modulus to the transverse one, it is found that the former ratio is smaller than the latter except in the case of 'Dalbergia Latifolia' It is known that the expansion of a body whether in the form of a very thin walled tube or a solid rod of the same dimension will be the same, so that the very thin walled rays, even though they are too weak to add to the strength of wood, add their expansion to that of the fibres The addition of a constant quantity representing the expansion of the rays to those of the fibres in the transverse and longitudinal directions will certainly reduce the value of this ratio, it being remembered that this ratio based upon its inverse relation to elasticity will be an improper fraction (i e, with numerator greater than the denominator) The exception in the case of 'Dalbergia Latifolia' is perhaps due to the large twisting and interlocking of the fibres of this wood which might tend to diminish the longitudinal expansion still further and thus increase this ratio Further the differences between these two ratios increase with diminishing value of the density showing that as the amount of fibrous material (which, by the way, will contribute more to the density

ie very thin walled, wide rays) diminishes, the effect of the ion of the rays becomes more and more pronounced

i The next point which deserves consideration is the result all the woods studied, 'a_2' is invariably larger than 'a' though solute value of the difference seldom exceeds about 8% mination of the photo-micrographs of the sections correspond- these coefficients shows that 'a_2' corresponds to the lateral ion of fibres frequently interrupted by layers of medullary hile 'a_3' corresponds except in the case of twisted fibres, to an uninterrupted layer of fibres Obviously in the former ie expansion of the fibre against the weaker rays can take nore easily but more than this is the fact that the expansion rays in their transverse direction is added on to that of the since 'a_2' corresponds to a direction normal to both the fibre e ray In the case of 'a_3', the uninterrupted arrangement fibres might impede mutual expansion and further, the rays parallel to this plane, their contribution towards expansion quite small

(iii) The last and perhaps the most interesting observation ut of the results is the remarkable effect of temperature mal expansion in the longitudinal and transverse directions. ows a more or less uniform increase in value with rising atures whereas 'a_2' shows a rapid fall in value It is further that nearabouts of 200°C the two coefficients tend to become The rapidity in fall of the transverse expansion with increasing ature, even suggests that wood, if it can retain its physical ies up to this limit, will probably cease to expand transversely 250°C or so, as though, before reaching this temperature, nsverse expansion of wood had reached its maximum value t no further appreciable expansion was possible with rise of ature

Any theoretical explanation of the thermal expansion of wood take into account the following important experimental facts

1. At ordinary temperatures, the transverse expansion is

several times larger than the longitudinal expansion i e, there is a large anisotropy of expansion

ii As the temperature rises the longitudinal coefficient goes on steadily but slowly increasing while the transverse coefficient rapidly diminishes in value

iii At temperatures approaching 200°C the anisotropy of expansion is negligibly small

For understanding the thermal properties of matter especially of the non-metallic kind in the solid state, Debye's conception is very helpful According to Debye, thermal energy is resident in matter as the energy of a system of elastic waves caused by the nuclear vibrations of the atoms constituting matter In the theory of specific heats, the thermal energy of a simple lattice like that of a metal is expressible in terms of Debye functions while in the case of a complex lattice, in addition to the Debye functions, the Einstein functions corresponding to characteristic oscillators will have to be taken into account also In the case of thermal expansion likewise, in the case of simple lattices it will be enough to consider the Debye functions on the basis of the Born-Gruneisen theory while for complex lattices it will be necessary to take into account the Einstein functions also But whatever oscillators may be considered, the application of quantum considerations to the energy distribution between the various nuclear vibrations, with the restriction that the elastic spectrum will be limited by the number of degrees of freedom N (=3Z) of the Z atoms constituting the system leads to the association of each vibration frequency with a definite quantity called its characteristic temperature The lower the frequency of oscillation the lower will be the characteristic temperature Near the characteristic temperature, any oscillator is as it were in a state of resonance and the bulk of the energy of the body will reside in such oscillators If a system consists of a number of groups of oscillators, each group consisting of a number of oscillators with characteristic temperatures lying close together, while the characteristic temperature varies considerably from group to group, then as the temperature rises with the supply of thermal energy, the group corresponding to the lowest characteristic temperature will be first excited and as the temperature rises above the highest characteristic temperature corresponding to this group, all the oscillators of this group would have reached the state corresponding to a statistical equipartition of energy and if more energy is supplied, the chances are that other groups previously not excited whose characteristic temperatures lie in the neighbourhood of the new temperature would pick up the additional energy and the lower frequency oscillators would be left more or less at a steady energy state It is very likely that the energy of increasing temperature will go into the fundamental states of the higher groups before any of the overtones of the lower groups get appreciably excited

Born[82] has shown that this conception will require a slight modification when applied to the case of anisotropic bodies According to Born, the Debye waves in an anisotropic medium will be propagated with three different velocities in the three principal directions of elasticity with three sets of overtones An extension of Born's theory has enabled Gruneisen to explain the otherwise incomprehensible phenomenon of a negative thermal expansion in certain directions of some crystals at low temperatures Gruneisen and Goens[83] studied the thermal expansion of hexagonal crystals at low temperatures and find that at these temperatures, the negative expansion takes place along the axes of maximum elasticity and as the temperature rises, the magnitude of the negative expansion goes on diminishing numerically, till after a certain range, the expansion ceases to be negative and becomes positive At low temperatures the excited oscillators will be those corresponding to low frequencies of oscillation and hence will be those in the direction of minimum elasticity The expansion in the direction of minimum elasticity corresponding to these oscillations will cause lateral contraction (in accordance with Poisson's ratio) in the direction of maximum elasticity and since the oscillations corresponding to this latter direction would not be excited at low temperatures, the observed effect will be a contraction in this direction With increasing temperature the oscillations in the latter direction will be excited and the expansions due to these oscillations will mask the lateral contraction due to the former effect and a positive coefficient is obtained Adenstedt[84] studying single crystal lattices has been able to confirm Gruneisen's theory and Erfling[85] has extended the experiment to a large number of substances at low temperatures In all these cases the crystal lattices chosen were comparatively simple and well-known A general survey of thermal expansion in relation to crystal structure is given by Megaw[86]

The application of the above theory to organic crystal lattices becomes more and more complicated since usually, organic lattices are much more complex than inorganic lattices and also because the actual amount of definite information on organic lattices is small In such a case it is more fruitful to correlate expansion not simply with the elastic anisotropy but also with the chemical structure of the molecules Fortunately even where elastic data are not correctly known, the molecular structure of many organic molecules is well-known on chemical or X-ray data Working on this basis, Robertson and Ubellohde[87] have investigated a number of inorganic and organic compounds with both ordinary and heavy hydrogen in the constitution and have found that in compounds containing hydrogen and hydroxyl bonds, there is marked anisotropy of expansion This is in consonance with the fact already considered in Section IV-I that in compounds containing hydrogen and hydroxyl bonds, there is marked anisotropy of elasticity

It now becomes easy on the basis of the above considerations to obtain a general explanation of the characteristics of the thermal expansion of wood, but before doing so it will be well to consider the effect of lignin on the thermal expansion of cellulose As we know, the structure is a hollow tube of cellulose sheathed in a co-axial lignin tube It is quite well-known that the coefficient of thermal expansion is the same for a material whether the cross-section is hollow or solid Hence of the two factors, viz., hollow structure and the surrounding lignin, which have been considered in the previous sections as modifying the properties of cellulose, it will only be lignin to be considered in connection with thermal expansion The effect of lignin, even though lignin is isotropic, will make itself felt differently on the longitudinal and on the transverse thermal expansions on account of the large anisotropy of cellulose Comparing the coefficient of expansion of lignin and wood in the longitudinal direction, we find the values are of comparable magnitudes, so that in the longitudinal direction, when expansion takes place, the cellulose portion and the lignin portion will expand more or less equally On account of the very large disparity in the strength of cellulose and lignin along the longitudinal direction any small difference in the expansions of the cellulose and lignin cannot exercise any appreciable influence on the expansion of the cellulose portion

The case of the transverse expansion will however be different In this direction the strength of cellulose is only about twice that of lignin and mutual interaction will be more pronounced Also, on account of the weak lateral binding in cellulose, the expansion in this direction of cellulose will be much greater than the expansion of lignin Since the relative strengths are of comparable magnitudes, lignin will exert a definitely restraining effect on the expansion of cellulose This is apparently the reason why the ratio of the transverse expansion to the longitudinal expansion in wood is less than the ratio of the longitudinal Young's Modulus to the transverse Young's Modulus This restraining influence of lignin will diminish with increase of temperature since at higher temperatures the lateral expansion of wood rapidly diminishes and becomes comparable to that of lignin and hence lignin does not exercise any appreciable differential action on cellulose with respect to direction

Now coming to a general consideration of the expansion of wood, it is well-known that the lignified cellulose tissue in wood is an elongated fibre with a length many times greater than the cross-dimensions and in such a case, the structure of the material will in a large measure determine the expansion Whether we consider the microscopic fibre of wood or the submicroscopic micelles which make up the fibre or the still smaller cellulose molecules which make up the micelles, it is found that the structure is distinctly in the form of a long thin rod These long thin rods under the supply of heat will behave like a system of linear harmonic oscillators absorbing energy The frequency of the transverse oscillations of such an oscillator will be much smaller than that of the longitudinal oscillations with corresponding lower characteristic temperatures for the lateral oscillations and higher characteristic temperatures for the longitudinal oscillations Hence at low temperatures corresponding to low energy states, it will mainly be the transverse oscillations corresponding to low energy levels that would be excited This energy of transverse oscillation is conserved as between the kinetic energy of the oscillator and the potential energy of strain in the transverse direction On account of the low value of Young's Modulus of the fibres in a transverse direction (or the weak hydrogen bonds in the case of the cellulose molecule) even a small energy will correspond to a large amplitude of oscillation, so that at low temperatures the transverse expansion is much greater than the longitudinal one

As the temperature rises with a continued supply of heat energy, the energy goes more and more into the longitudinal mode of vibration since transverse oscillations at these higher temperatures would have already reached the condition of equipartition corresponding to their frequencies Thus the lateral amplitude will, as it were, reach a stationary state while the increasing energy of the longitudinal oscillations with increasing temperature will give this expansion an increasing value The decrease of Young's Modulus with increasing temperature might help to augment the amplitude of the longitudinal vibration and thereby help further to increase this coefficient with temperature

It will be interesting to observe if other fibrous material, as for instance asbestos, shows a similar behaviour to wood

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