EFFECTS OF BEATING AND WOOD QUALITY ON RADIATA PINE KRAFT PAPER PROPERTIES

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ABSTRACT

Effects of beating on radiata pine (**Pinus radiata** D. Don) kraft fibre properties are assessed in terms of fibre dimensions, and surface and intrawall structure. Wood quality effects are discussed with reference to pulps and handsheets prepared from young, mature and compression wood, and earlywood and latewood samples.

Mature earlywood, latewood and composite pulps have similar handsheet properties except for elastic modulus and tear factor. Corresponding young wood pulps give greatly different paper properties. The range of young wood paper properties is associated with readily flattened earlywood fibres in which beating produces extensive intrawall dislocation and layer separation.

Compression wood paper properties vary with fibre dimensions and density in the same way as normal wood, except for stretch. Exceptionally high compression wood stretch values are associated with the unique intrawall structure of reaction wood fibres, i.e., spiral checking within the S_2 layer, absence of an S_3 layer and an anomalous S_1 layer.

Breaking length and scattering coefficient are affected by beating to similar extents which indicates that both parameters are equally affected by web consolidation and intra- and interfibre bonding. Apparent density, however, appears to be affected only by the nature of fibre packing within a sheet.

Most paper properties attain maximum values after extended beating treatments. These maxima coincide with a scattering coefficient of about 150 cm^2/g which indicates that maximum fibre flattening, and intra- and interfibre bonding occur at this scattering value. Any further decrease in the number of light interreflections is explained by the filling of interfibre voids with fines.

INTRODUCTION

Effects of laboratory beaters on the morphology, and surface and intrawall structure of several types of radiata pine (*Pinus radiata* D. Don) kraft fibres have been described elsewhere (Kibblewhite, 1972 a-c). Pulps were beaten in a PFI mill, a Lampen mill and a Valley beater and examined in unbonded, partly bonded and standard paper mats by scanning and transmission electron microscopy.

In this paper the properties of handsheets prepared from earlywood, latewood, compression wood, young wood (rings 1-10) and mature wood (rings 20-30) radiata pine kraft fibres are examined in terms of wood and fibre characteristics, and PFI mill beating. Effects of different beaters will be described in a further paper. Literature concerning the effects of wood quality on paper strength and optical properties has been discussed in reviews by Dinwoodie (1965, 1966), Tasman (1969) and Van den Akker (1970).

EXPERIMENTAL

Pulp preparation and a method for the measurement of pulp fibre length have been described previously (Kibblewhite, 1972a).

The mature wood sample consists of the outer 10 of 30 growth layers in roundwood billets taken from the same two 44-year-old radiata pine trees in Kaingaroa Forest from which the young wood sample was obtained (Kibblewhite, 1972a). The compression wood sample was taken from the butt sweep of a tree on the same site and consisted of the outer 10 of 35 growth layers in the roundwood billet.

Transverse tracheid dimensions and wood density values were obtained by the methods of Harris (Harris, 1969a, b, and Kibblewhite, 1971).

Lignin and carbohydrate contents of the wood and pulp samples were determined by the methods of Kerr (1970) and Harwood (1971) respectively. Composition data for the wood samples are listed elsewhere (Kibblewhite, 1971).

The number of tracheids per gram and the external tracheid specific surface were calculated using the transverse dimension and fibre length data. The number of fibres per gram of pulp is equal to the reciprocal of (cross-sectional tracheid wall area) × (fibre length) × (wood substance density). The calculated external fibre specific surface is equal to twice the (radial plus tangential tracheid diameter) × (fibre length) × (number of fibres per gram). Wood substance density is taken as 1.5 g/cm^3.

Physical evaluation data were obtained on 60 g/m^2 handsheets prepared according to Appita method 203 m-62. Tear factor, burst, bulk and air-resistance values were obtained as described in Appita method P208 m-64. Pulp freeness was determined according to Appita method P206 m-61. Breaking length, stretch, tensile energy per unit area, and elastic modulus were determined with a table model Instron instrument. Determinations were made on 15 mm-wide strips of gauge length 100 mm and an extension rate of 10 mm/min. Scattering coefficient was determined on 60 g/m^2 handsheets by the SCAN procedure using an Elrepho reflectance meter. Pulps were beaten in a PFI mill at a stock consistency of 10% (Kibblewhite, 1972a).

RESULTS

Wood, Tracheid and Fibre Properties

The radiata pine pulps were obtained from a wide range of wood types and have very different tracheid and fibre properties (Tables 1 and 2). The terms tracheid and fibre refer to xylem elements in wood and pulp respectively.

There are more tracheids per gram in young wood than in the mature normal or compression wood samples. For any wood type, earlywood and latewood samples from a given growth layer contain the same number of tracheids per unit mass. Wall thickness increases with tree age but tracheid diameter does not. Tracheids in the eighth (young wood) and twenty-fifth (mature wood) growth layers from the pith have similar diameters. Differences in compression wood (latewood and earlywood) samples are small but wall thickness and density values are high compared with those of normal wood.

The weighted mean density of the young wood sample is similar to that of the

TABLE 1—Wood and tracheid characteristics

Wood sample	Growth layer from bark	Tangential tracheid diameter (μm)	Radial tracheid diameter (μm)	Tracheid wall thickness (μm)	No. tracheids per gram	Geometrical external tracheid specific surface (cm^2/g)	Wood density (g/cm^3)	Fibre density* (g/cm^3)
Young								
Earlywood	7	29.6	37.8	2.1	10×10^5	3370	0.30	0.36
Latewood	7	26.0	23.1	2.7	11×10^5	2700	0.60	0.58
Young								
Earlywood	2	33.7	49.3	2.4	7×10^5	2906	0.36	0.34
Latewood	2	30.4	26.5	3.7	7×10^5	1992	0.69	0.67
Mature								
Earlywood	5	35.1	46.9	2.9	5×10^5	2460	0.39	0.40
Latewood	5	30.7	32.2	4.0	5×10^5	1888	0.68	0.66
Compression								
Earlywood	5	33.0	44.5	3.6	5×10^5	2040	0.46	0.51
Latewood	5	28.0	27.7	4.2	6×10^5	1872	0.73	0.76

* (Cross-sectional wall area/fibre cross-sectional area) $\times$ 1.5

The value 1.5 represents the wall substance density assumed (Harris, 1969a)

TABLE 2: Pulp and fibre characteristics

Pulp sample	Mean sample wood density (g/cm^3)	Percent of composite sample	Fibre length (mm)		Lignin (Wood %)	Sugars % in wood hydrolysates			
			Unbeaten	Beaten*		Glucose†	Mannose	Arabinose	Xylose
Young									
Earlywood	0.35	55	2.5	2.5	5.9	85.5	4.6	1.0	8.9
Latewood	0.65	45	2.6	2.5	5.0	85.5	5.7	1.0	7.8
Composite	0.45	—	2.5	—	5.6	84.4	6.4	1.0	8.2
Mature									
Earlywood	0.39	44	3.0	—	7.5	85.6	6.1	0.9	7.4
Latewood	0.66	56	3.2	—	4.8	87.0	5.6	0.7	6.7
Composite	0.50	—	3.1	—	6.1	86.0	6.0	0.9	7.1
Compression									
Composite	0.55	—	2.8	—	7.5	87.0	3.8	1.0	8.2

* Beaten in a PFI mill at 10% consistency for 15 000 rev.

† Glucose refers to combined glucose-galactose contents.

eighth growth layer from the pith (Tables 1 and 2). Weighted mean densities of the earlywood and composite samples of young wood are less than those of corresponding mature wood samples. Also, the overall density range of the three young wood pulps is greater than that of mature wood.

Preferential shortening by beating of mature latewood fibres is assumed on the basis of beaten young wood fibre length data (Table 2). On this basis, the fibre length of beaten young wood pulps is about 2.5 mm and that of mature wood fibres about 3.0 mm.

Density, dimension and composition data presented in Tables 1 and 2 are similar to those given in the literature (Kibblewhite, 1971). However, the compression wood sample used for pulping requires further comment. Although most of the characteristics of compression wood are well developed (macroscopic appearance, thick cell walls and chemical composition), tracheids are not particularly rounded and intercellular spaces are infrequent. These last two features are regarded as typical of well developed compression wood (Dadswell *et al.,* 1958 and Kollman *et al.,* 1968), although they are often absent in radiata pine.

Paper Strength and Optical Properties

Young, mature and compression wood pulps each give different handsheet densities at the same number of beating revolutions (Fig. 1). Because mature and young latewood samples have similar wood densities (Table 2), the density variation between pulp sheets is probably related to differences in fibre length. Scattering coefficient values for the unbeaten pulps are widely separated (Fig. 2) and indicate effects of different fibre dimensions and specific surfaces (Tables 1, 2). Beating rapidly minimises these differences and the curves for all seven pulps tend to coincide after about 15,000 rev in the PFI mill. Compared with young latewood and the mature wood pulps, the air-resistance of handsheets prepared from the young earlywood pulp increases rapidly with beating (Fig. 3, Table 3).

Breaking length and stretch increase linearly with sheet density (Fig. 4). Tensile energy is linearly related to sheet density (Fig. 5) and appears to be independent of the fibre characteristics listed in Tables 1 and 2. Compared with breaking length and stretch (Fig. 4), elastic modulus is highly sensitive to changes in pulp quality (Fig. 6). Each pulp has a separate and approximately linear modulus-density relation. The long-fibred mature wood pulps give handsheets with the best tear properties (Fig. 7).

DISCUSSION

Apparent Sheet Density

Effects of wood and fibre density on pulp handsheet density are obscure. The handsheet densities of the three young wood pulps cover a much wider range than those made from mature wood. The short length, low density and extremely thin walls of young earlywood fibres all contribute to the very high densities of handsheets prepared from this pulp. The low apparent density of handsheets prepared from mature earlywood pulp is probably related to a wide range of fibre densities. Earlywood tracheid diameter and wall thickness measurements are made at the centre of the "plateau" of low density wood (Fig. 8). For young earlywood a definite plateau exists, and the earlywood sample is approximately homogeneous with respect to fibre density. In contrast, a definite

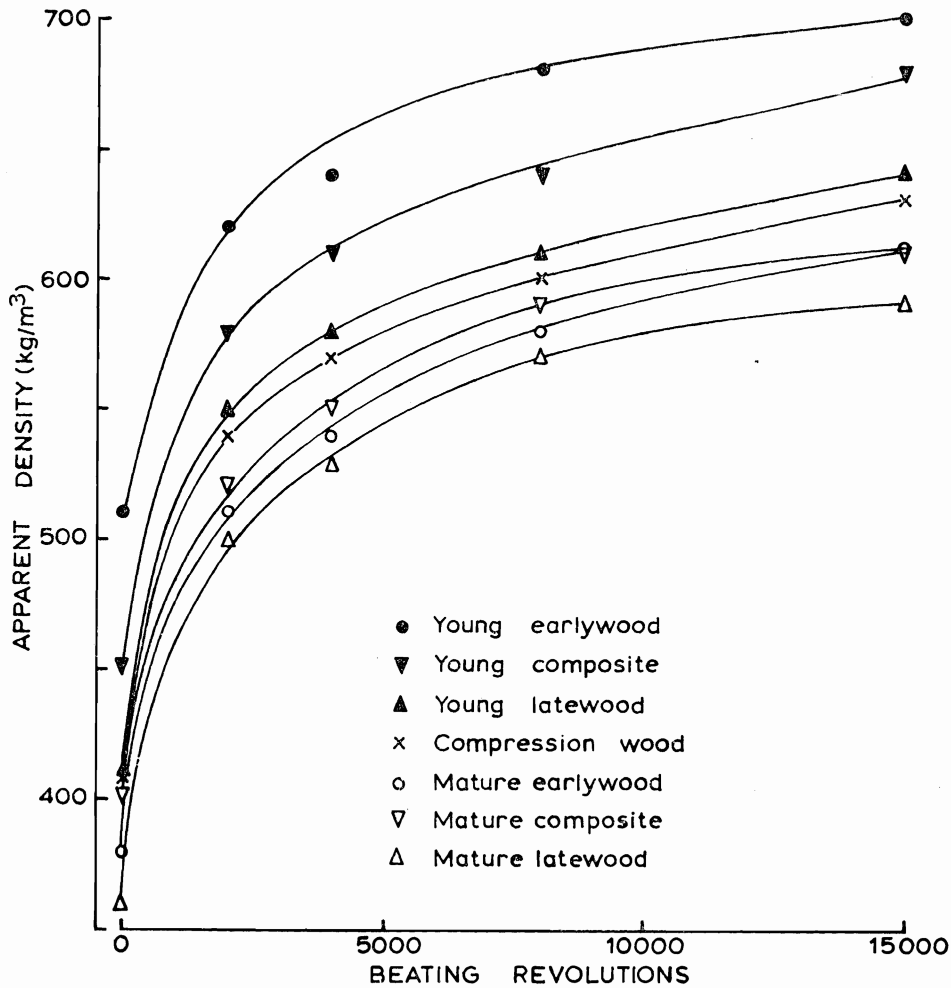

FIG. 1—Sheet density and beating revolutions.

earlywood plateau is absent in mature wood and wood density increases throughout the earlywood portion of a growth layer. Consequently, mature earlywood transverse fibre dimensions are extremely variable (Fig. 9) and data listed in Table 1 represent maximum diameter and minimum wall thickness values. Similarly, the mature earlywood density value of 0.39 g/cm^3 (Table 2) is a minimum rather than a mean value. On a relative basis, the mature and young latewood, and the young earlywood mean sample density values listed in Table 2 appear to be valid. A homogeneous mature earlywood sample comparable with young earlywood does not exist.

The numbers of fibres per gram of compression wood are similar to those of mature wood (Table 1) and the apparent density of handsheets prepared from the compression wood pulp lies between those of the mature and young wood pulps (Fig. 1). As in the mature and young wood pulps, the relative sheet density of the compression wood pulp can be attributed to differences in fibre length.

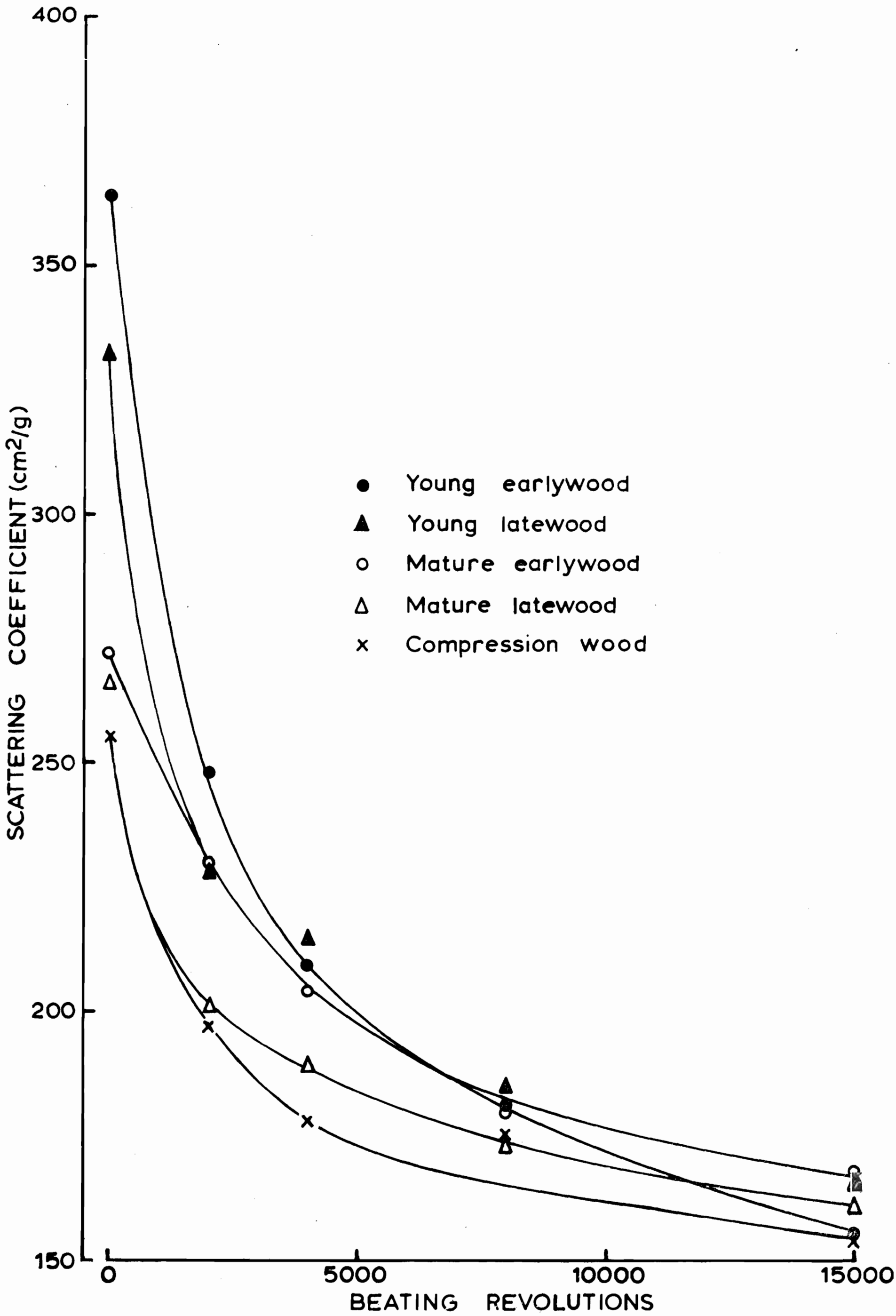

FIG. 2—Scattering coefficient and beating revolutions.

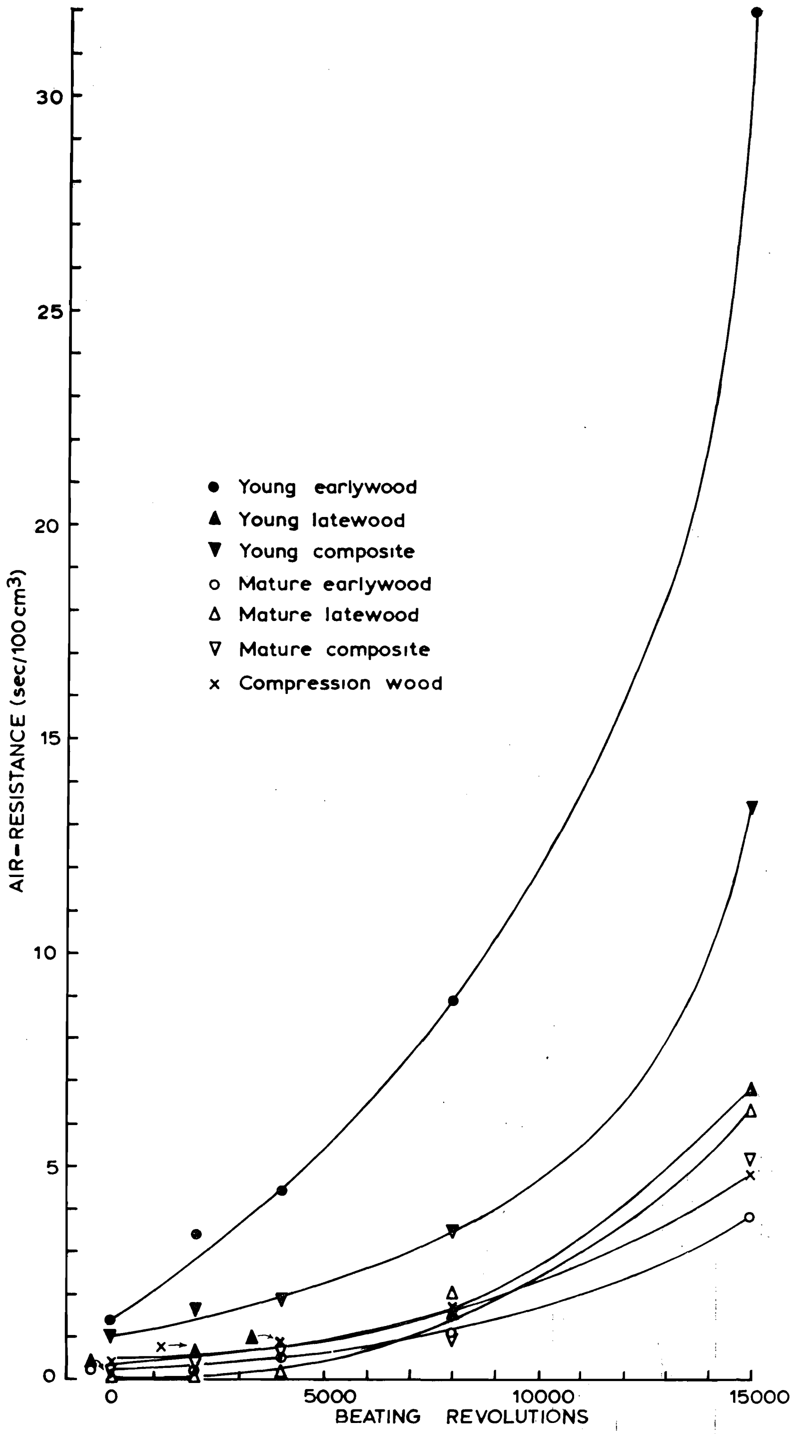

FIG. 3—Handsheet porosity and beating revolutions.

TABLE 3: Physical Evaluation Data for Pulps Processed in a PFI Mill at 10 Percent Consistency

Pulp	Beating rev	Freeness Csf	Tear factor	Apparent sheet density kg/m^3	Scattering coefficient cm^2/g	Burst factor	Air resistance sec/100 cm^3	Breaking length km	Stretch %	Tensile energy per unit area J/m^2	Elastic modulus N/mm^2
Young:	zero	736	228	510	364	31	1.4	4.4	2.4	44	2,700
Earlywood	2,000	734	146	620	248	58	3.4	6.7	3.0	82	4,300
	4,000	719	115	640	209	66	4.4	6.9	2.9	82	4,700
	8,000	682	115	680	181	80	8.9	8.5	3.7	124	4,800
	15,000	588	108	700	155	85	31.9	8.7	3.7	129	5,200
	15,000	653	113	700	175	-	-	8.5	3.7	125	4,800
	30,000	279	106	740	142	97	464.3	9.6	3.7	144	5,400
	55,000	63	94	780	106	110	>20 min	10.4	4.1	165	5,900
	55,000	124	98	770	144	-	-	10.1	4.2	159	5,700
	55,000	f154	105	760	144	-	-	10.2	4.2	161	5,500
	zero	763	151	410	332	13	0.2	2.2	1.3	11	1,400
Latewood	2,000	762	235	550	228	32	0.8	4.1	2.0	32	3,000
	4,000	754	217	580	215	40	1.0	4.9	2.2	42	3,200
	8,000	711	207	610	185	53	1.6	6.3	2.8	70	3,700
	15,000	534	183	640	166	64	6.8	7.0	3.0	79	3,900
	30,000	200	154	670	154	73	143.0	8.6	3.6	118	4,300
	55,000	37	121	740	78	97	>20 min	9.6	3.7	140	5,000
	zero	741	198	450	338	18	1.0	3.0	1.7	22	1,900
Composite	2,000	744	226	580	261	41	1.6	5.2	2.6	57	3,300
	4,000	739	189	610	205	53	1.8	6.1	2.9	67	3,800
	8,000	700	148	640	175	64	3.4	7.6	3.2	94	4,400
	15,000	586	135	680	154	77	13.4	8.8	3.6	120	4,900

Mature:	zero	761	167	380	272	11	0.2	2.1	1.0	9	1,300
Earlywood	2,000	768	299	510	230	27	0.3	4.1	1.7	28	2,800
	4,000	752	312	540	204	35	0.6	5.2	2.0	43	3,300
	8,000	754	244	580	181	51	1.1	6.3	2.5	60	3,800
	15,000	677	211	610	168	63	3.8	7.5	2.7	80	4,100
	55,000	27	116	720	110	84	>20 min	10.0	4.0	154	5,100
	zero	764	138	360	266	8	0.1	1.9	1.0	8	1,200
Latewood	2,000	760	262	500	201	23	0.1	3.8	1.7	25	2,600
	4,000	746	330	530	189	31	0.2	4.6	2.0	36	3,000
	8,000	705	340	570	174	44	2.0	6.1	2.4	59	3,400
	15,000	491	255	590	161	59	6.3	7.0	2.8	71	3,500
	55,000	10	115	700	151	108	>20 min	9.7	3.5	127	4,300
	zero	741	158	400	261	11	0.2	2.2	1.1	9	1,500
Composite	2,000	768	286	520	210	24	0.3	4.2	1.7	28	3,100
	4,000	774	308	550	186	34	0.7	5.1	2.0	41	3,600
	8,000	738	290	590	167	51	1.0	6.4	2.4	62	4,100
	15,000	586	251	610	155	61	5.1	7.6	2.8	87	4,600
Compression wood:	zero	753	170	410	255	14	0.4	2.2	1.5	14	1,300
Lignin - 7.5%	2,000	750	262	540	197	32	0.8	4.0	2.6	43	2,600
	4,000	745	267	570	178	39	0.8	4.5	3.0	54	2,700
	8,000	711	232	600	175	54	1.5	5.6	3.2	75	3,400
	15,000	618	188	630	154	63	4.8	6.4	3.7	95	3,400
	zero	756	278	460	-	29	0.1	3.6	2.1	30	2,100
Lignin - 9.5%	2,000	750	250	570	-	42	0.2	4.6	2.8	52	2,800
	8,000	718	220	610	-	57	1.3	6.0	3.5	86	3,400
	15,000	622	206	630	-	63	3.4	6.3	3.8	97	3,500

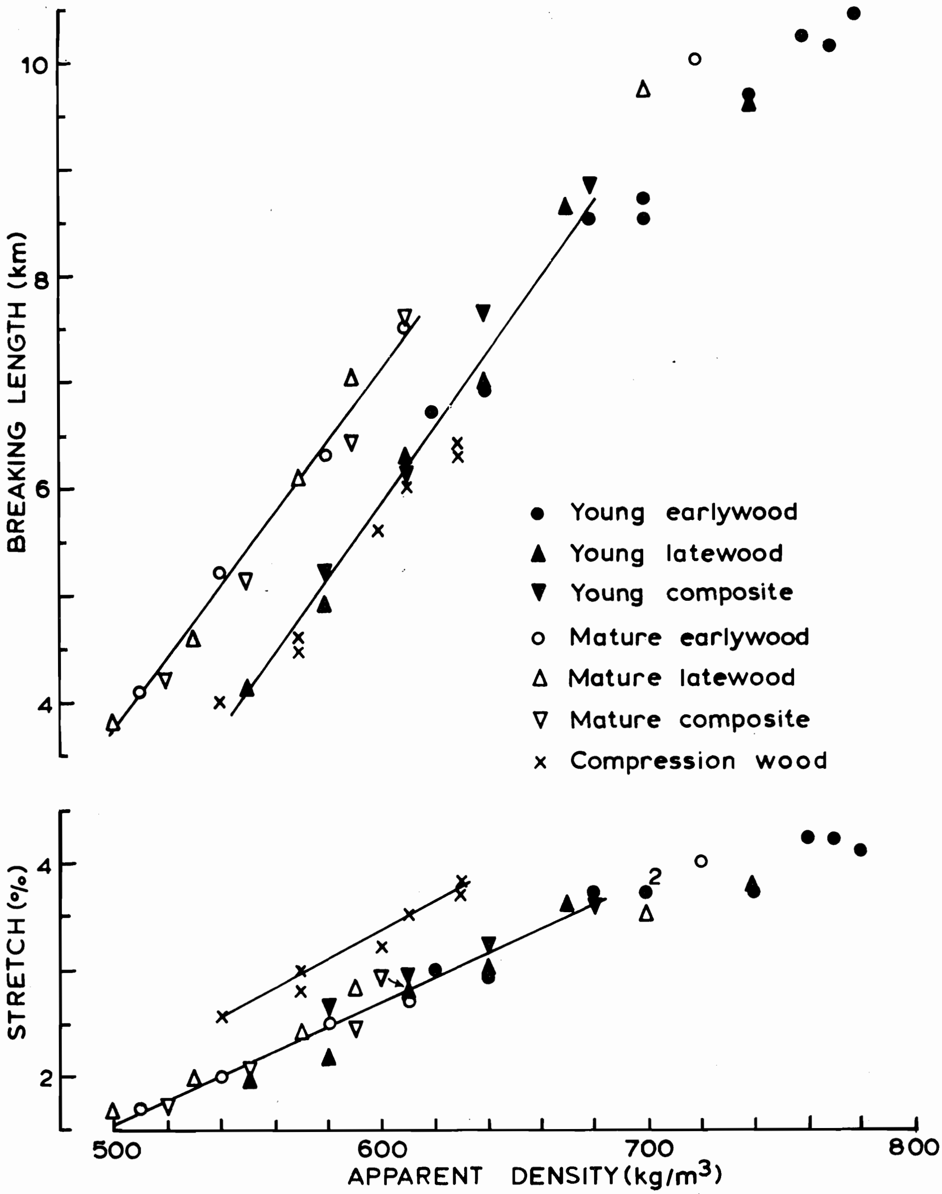

FIG. 4—Breaking length, stretch and density.

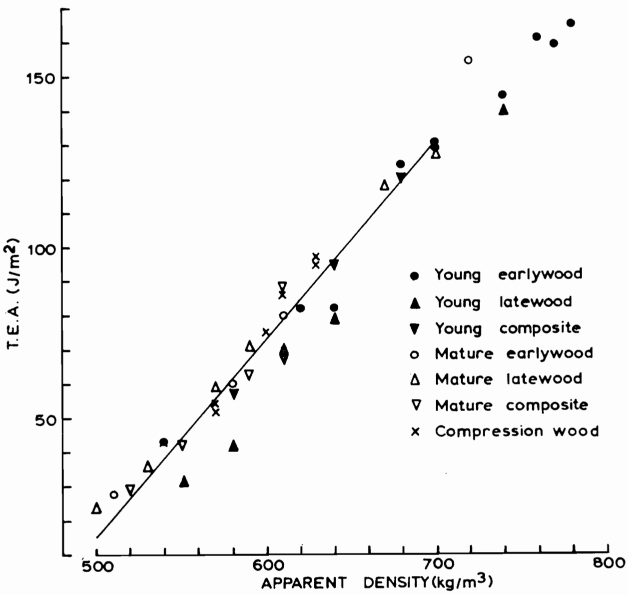

FIG. 5—Tensile energy and density.

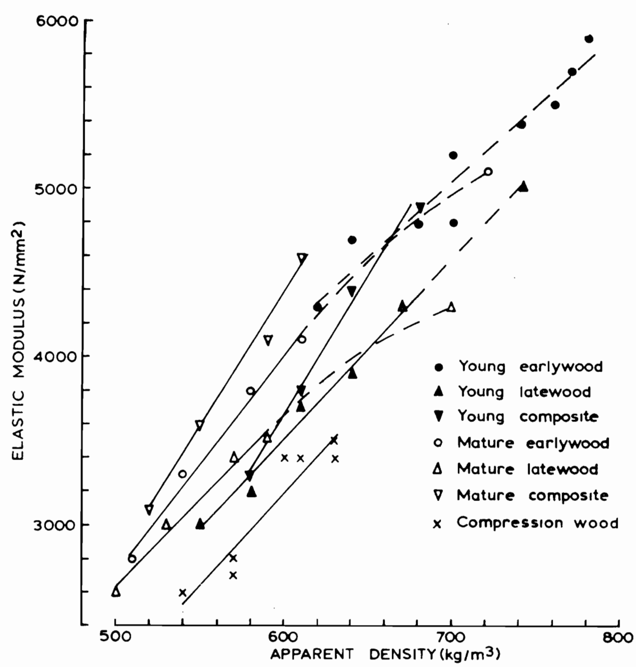

FIG. 6—Elastic modulus and density.

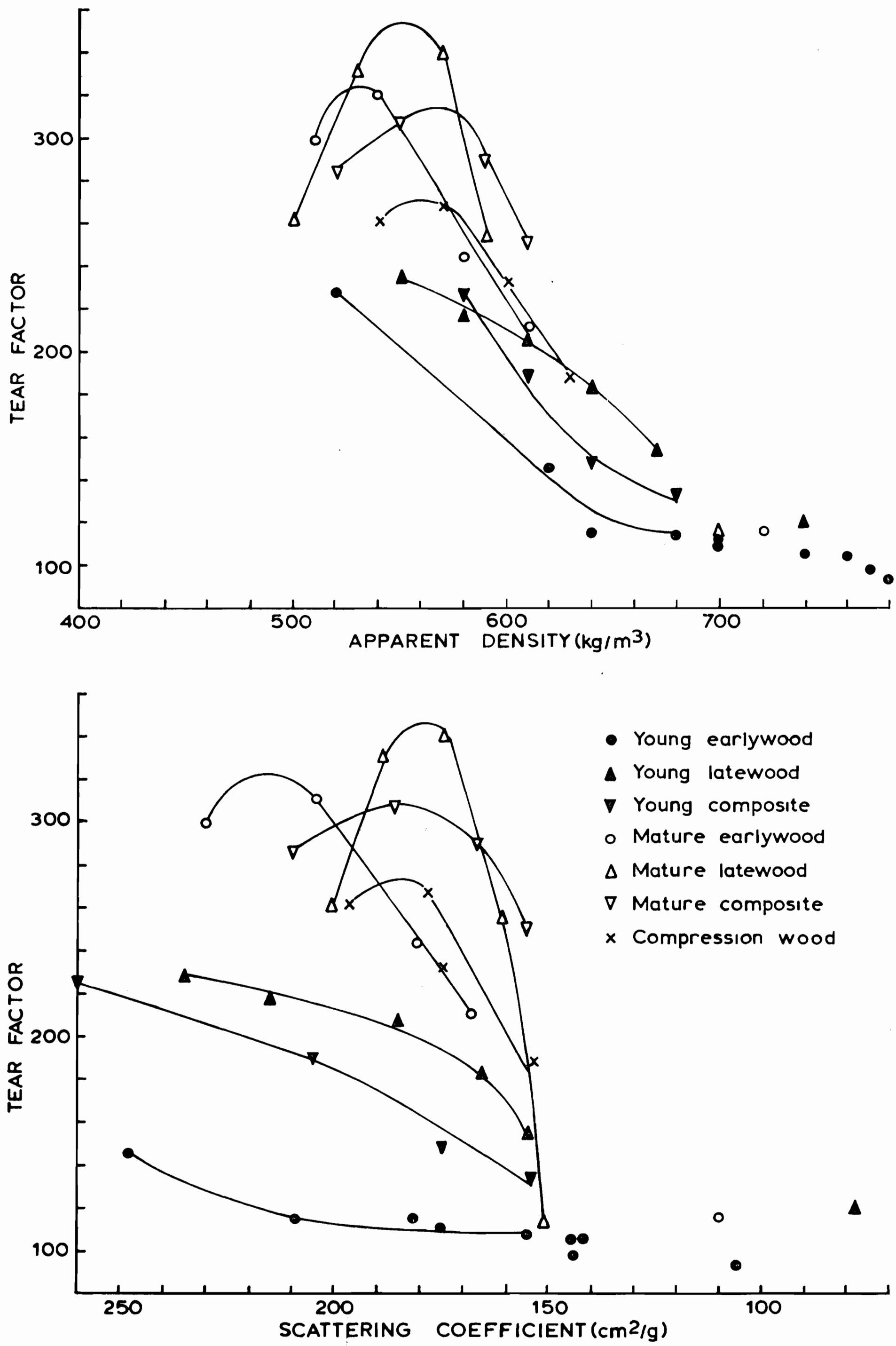

FIG. 7—Tear factor, density and scattering coefficient.

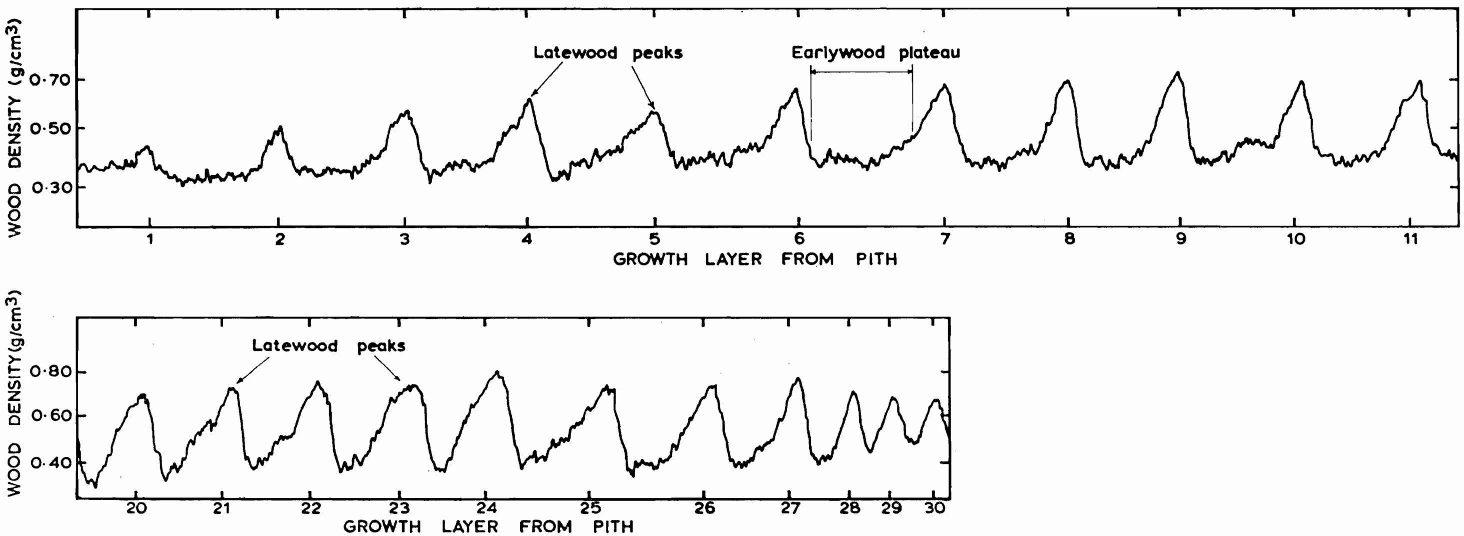

FIG. 8—Typical young and mature wood densitometer charts.

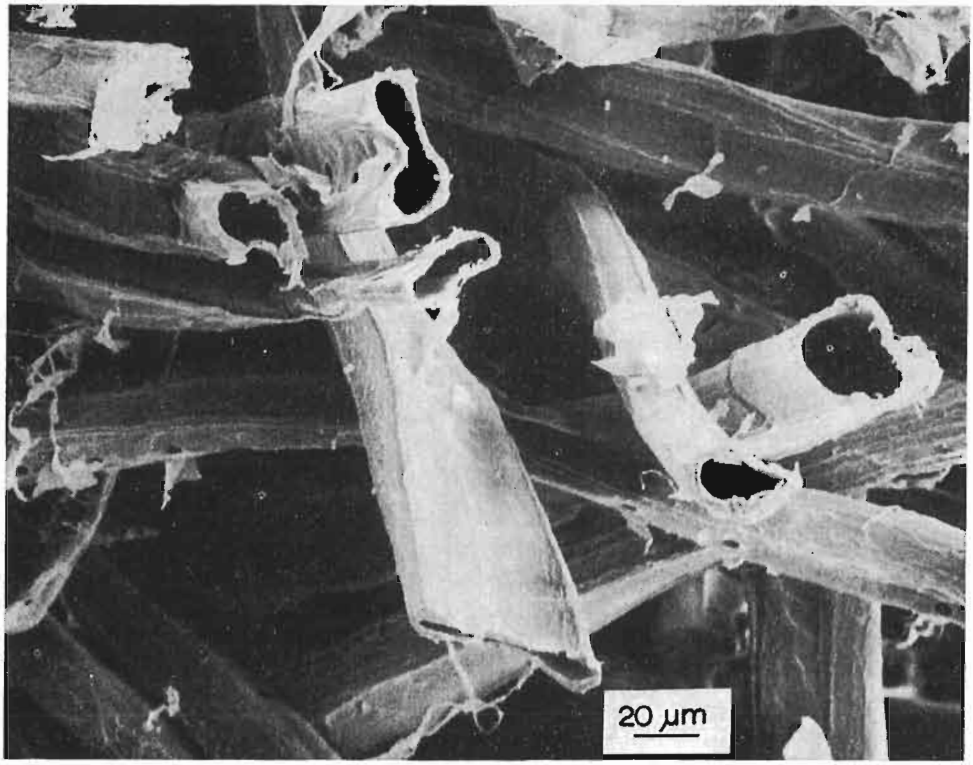

FIG. 9—Cross sectional view of mature earlywood fibres with a wide distribution of transverse dimensions.

Optical Light-scattering

Because the compositions of the seven pulps are similar (Table 2), the relative scattering coefficient values of Table 3 should be comparable. Hartler and Rennel (1967), and Balodis (pers. comm.) showed scattering values for unbleached pulps to be low relative to bleached stock.

The scattering coefficient of young earlywood pulps decreases much more rapidly with beating than in other pulps examined (Fig. 2). Although the low density young earlywood fibres have initially high external specific surfaces (Table 1), they have extremely thin walls and are readily flattened and made flexible by beating (Kibblewhite, 1972a, c) and hence scattering coefficient rapidly decreases. Conversely, scattering values decrease slowly with the stiffer latewood and mature earlywood pulps which have low initial specific surfaces (Table 1) and are not readily flattened by beating (Kibblewhite, 1972c).

A direct relation between scattering coefficient and sheet density is not obtained (Fig. 10). Whereas density is a measure of fibre packing within a sheet, scattering coefficient indicates the extent of intra- and interfibre bonding. The different fibre characteristics which influence apparent density and scattering coefficient are explained with reference to the linear regions of the young latewood and mature latewood curves

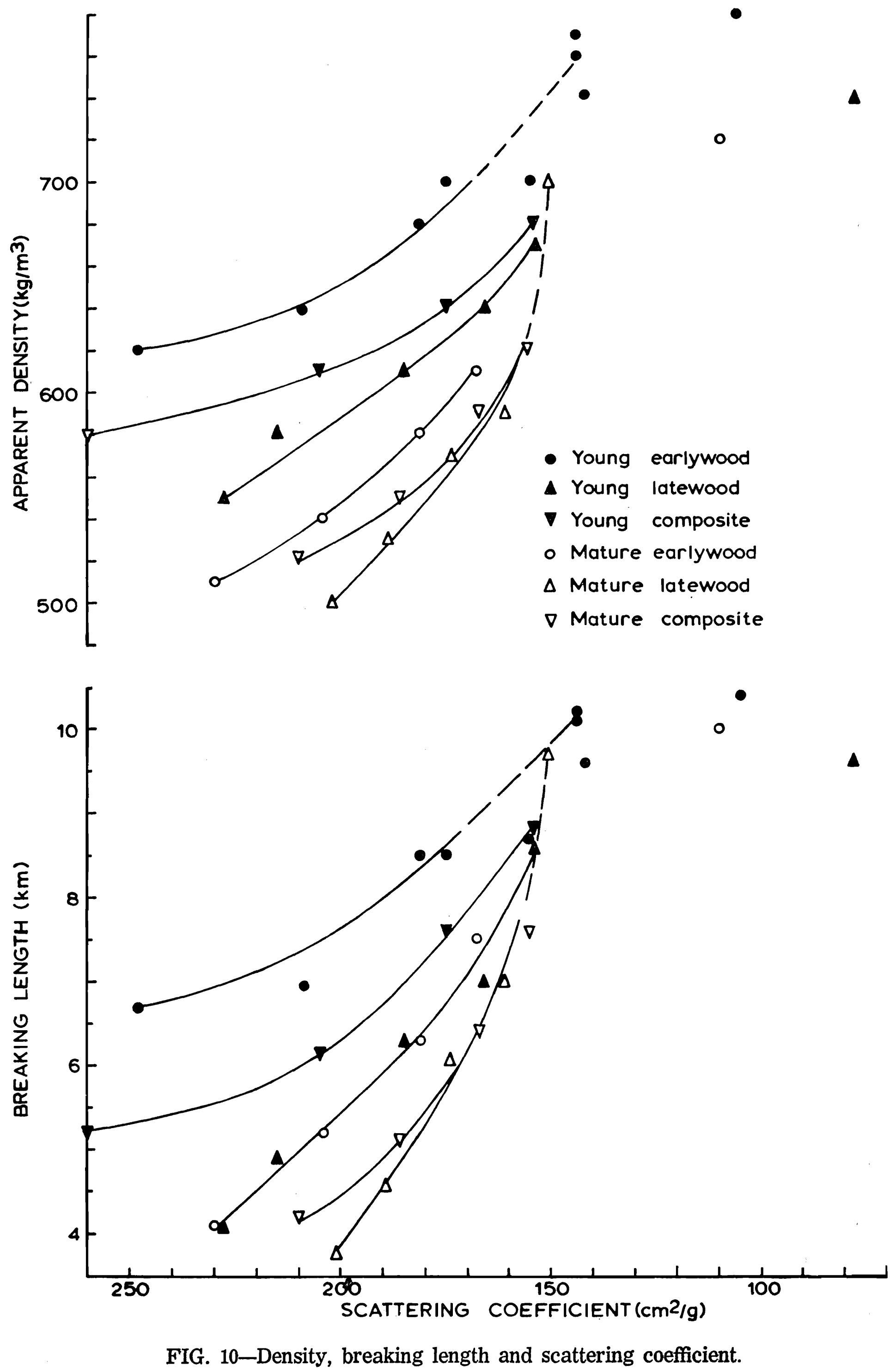

FIG. 10—Density, breaking length and scattering coefficient.

(Fig. 10). Fibres in both pulps have similar densities and external specific surfaces and, therefore, the wide separation of the mature and young latewood curves is probably caused by different numbers of fibres per gram (Table 1). Differences in handsheet apparent density (Fig. 1) and the number of fibres per gram are associated with the greater length of mature wood fibres (Table 2). The number of interfibre contacts and air-fibre interfaces are therefore greater in the more densely packed, young latewood handsheets. Consequently, a disproportionately greater numbr (relative to sheet density) of light interreflections occur between young latewood fibres.

Beating causes the initially widely separated curves of Fig. 10 to coincide at scattering values of about 150 to 160 cm^2/g. These data indicate that, throughout beating, intra- and interfibre bonding takes place until a "bonding maximum" is reached beyond which sheet density and breaking length increase only slightly. Any further decrease in scattering values is attributed to the filling of interfibre voids with fines material without increasing paper strength and sheet density significantly (Fig. 10).

At scattering values greater than 150 cm^2/g, the amount of fines is small in the radiata pine kraft pulps (Fig. 11) (Kibblewhite, 1972a, c). Most of the partly attached fragments visible in the unpressed mat of Fig. 11 appear bonded to fibre surfaces in standard handsheets (Kibblewhite, 1972b). Fines only appear to fill interfibre voids at scattering values less than 150 cm^2/g (Fig. 12).

At scattering values equal to, and less than 150 cm^2/g, the thickness of the radiata pine kraft handsheets is probably somewhat independent of fines content and beating time (Fig. 10, Table 3). At these scattering values, the degrees of fibre flattening and interfibre bonding remain essentially constant and sheet caliper and consequently sheet density are changed only slightly as material is removed from fibre walls (by beating) and deposited as fines in interfibre voids (Figs. 10, 11, 12). This deposition of fines to fill interfibre voids reduces the number of light-scattering surfaces, which consequently decreases scattering coefficient.

Scattering data are closely correlated to breaking length and beating time (Figs. 2, 10). Except for the young earlywood data, the order and general trends of each pulp are similar in the two figures. This is particularly true for the young latewood and mature earlywood data which fall on identical curves.

Porosity

Compared with young latewood and the mature wood pulps, the air-resistance of handsheets prepared from the young earlywood pulp increases very rapidly with beating (Fig. 3, Table 3). Although the relatively high air-resistance values of the young earlywood pulp can be attributed to highly flexible fibres (Kibblewhite, 1972a, b, c), fines probably also have an effect. Beating in the PFI mill penetrates the surfaces of young and maturewood pulps to similar extents (Kibblewhite, 1972a, c). Therefore, because of a higher external specific surface (Table 1), beaten young earlywood pulps contain more fines than mature earlywood. Because of variability within the mature earlywood sample (Figs. 8, 9), the specific surface listed in Table 1 is a maximum value. Consequently, differences in specific surface values and, therefore, the amounts of fines produced by beating the two earlywood pulps are greater than indicated in Table 1. The relatively high air-resistance of the young composite sample can be attributed to the high percentage (55% o.d.) of thin-walled earlywood fibres (Table 2). Differences between the

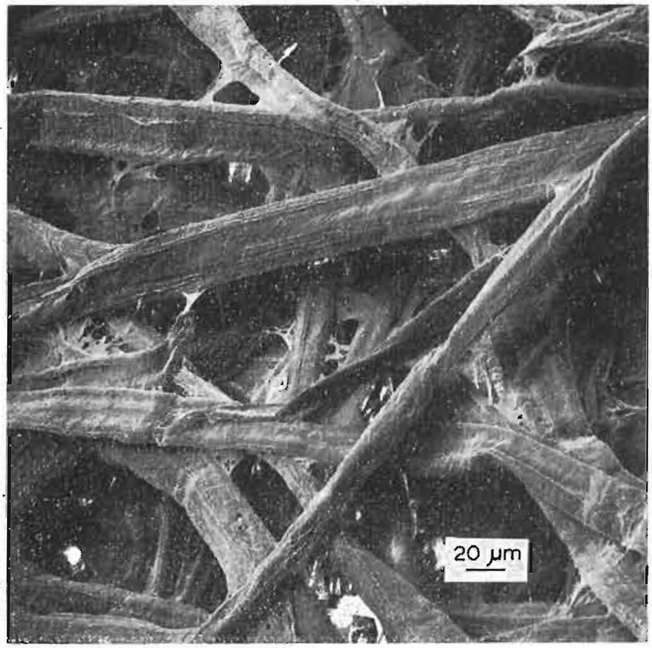

FIG. 11—Young latewood pulp in an air-dried, unpressed mat (Kibblewhite, 1972a, b). Pulp beaten for 15,000 revolutions in a PFI mill.

FIG. 12—Young latewood pulp in an air-dried, unpressed mat (Kibblewhite, 1972a, b). Pulp beaten for 55,000 revolutions in a PFI mill.

compression wood, young latewood, and the three mature wood pulps (Fig. 3) are probably insignificant.

Tensile Properties

For apparent density values less than 700 kg/m^3, breaking length increases linearly with web consolidation (Fig. 4). The degrees of fibre flattening, web consolidation and the area of interfibre bonds probably do not increase significantly beyond values of 700 kg/m^3 (Fig. 10). Analysis of data listed in Tables 1 and 2 indicates that differences in young and mature wood breaking length values (Fig. 4) are related to differences in fibre length. For a given apparent density, maturewood breaking lengths are greater by about 1 km. Whereas each of the three youngwood pulps have very different breaking lengths, those of the three mature wood pulps are similar. This concurs with the apparent density data discussed in relation to Figs. 1, 8, 9.

For a given handsheet density, compression wood stretch values are higher than those of the six normal wood pulps by about 0.5 units (Fig. 4). Deviation of the compression wood values from the normal wood curve is probably associated with the unique characteristics of reaction wood fibres, i.e., absence of an S_3 layer, spiral checking within the S_2 layer (Dadswell *et al.,* 1958 and Kollmann *et al.,* 1968) and an anomalous S_1 layer (Kibblewhite, 1972c). It is unlikely that the high reaction wood stretch is caused by the low microfibril angle of compression wood fibres because of the wide variation in this parameter in normal, young and mature, and earlywood and latewood fibres (Kollmann *et al.,* 1968 and Watson *et al.,* 1964). Similarly, an effect of different compositions (Table 2) is excluded because the data used in Fig. 4 refer to two compression wood pulps with different lignin contents (Table 3). Compression wood stretch values correspond to those of the young composite sample when compared at the same beating and scattering values (Table 3). Therefore, compared with normal wood, the unique intrafibre characteristics of compression wood allow paper stretch to be somewhat independent of fibre dimensions and fibre density.

For a given beating treatment, fibres with similar lengths and variable densities develop identical paper stretch. High stretch values are obtained with the young earlywood fibres where microcompression dislocations are developed by beating (Kibblewhite, 1972c) (Fig. 4). The similar stretch values of the young latewood and mature wood pulps are probably associated with the slow development of microcompressions in these relatively thick-walled fibres.

Tensile energy, the integral of the stress-strain curve, appears independent of fibre characteristics. When this parameter is plotted against apparent density, all points are on or close to the same regression line (Fig. 5). Like apparent density and breaking length (Fig. 10), maximum stretch, tensile energy and elastic modulus values appear to occur at scattering values of about 150 cm^2/g (Table 3).

Tear Factor

Although young earlywood pulps do not show the typical initial rise in tear with beating, young composite and latewood sheets show a slight increase (Fig. 7). The high apparent sheet density of the young earlywood and to a lesser extent the young latewood pulps accounts for this behaviour (Fig. 1). Lightly beaten mature and compression wood pulps have relatively low apparent sheet densities ($<$ 600 kg/m^3) and the typical initial rise in tear factor is evident (Fig. 7). Tear factor is not decreased by beating to values much below 100 units (Fig. 7). This is the value at which maximum interfibre bonding is developed (Fig. 10).

Compared with breaking length, stretch and tensile energy (Figs. 4, 5), tear values of each mature wood pulp are distinctly different. Highest values are obtained with the stiffer and denser mature latewood fibres.

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