Hardwood market kraft fibre and pulp qualities

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SUMMARY

Species compositions, fibre qualities and handsheet properties were assessed for a wide range of hardwood bleached market kraft pulps from different geographic locations. Ten Eucalyptus spp. pulps were examined (E. regnans(1)), (E. grandis(2)) and (E. globulus(7)) as well as eight birch, one aspen, and four mixed hardwood furnishes.

The eucalypt fibres were slender, short, generally of low coarseness; the pulps contained considerably more fibres per unit mass than corresponding birch, mixed hardwood or aspen furnishes. Eucalypt fibre qualities varied greatly depending on their origin or company of manufacture. The seven E. globulus furnishes were divided into two groupings depending on fibre quality. The two E. grandis furnishes could be separated on fibre quality grounds with one pulp fitting into each of the E. globulus groupings. Similar variabilities were found for the eight birch and four mixed hardwood furnishes, although they were of sufficiently similar fibre quality to allow grouping into birch and mixed hardwood categories.

The E. regnans fibres had the thinnest walls, and were slender and of very low coarseness. These fibre qualities gave a high potential for fibre collapse, high relative number of fibres per unit mass, and unique handsheet optical properties for the E. regnans furnish.

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To better understand interactions between different softwood and hardwood fibre types, their papermaking potentials and furnish blend properties, the fibre qualities and handsheet properties of a wide range of bleached market kraft pulps need to be characterized. In previous studies fibre and pulp qualities were determined for softwood market kraft pulps from a wide range of geographic locations(1). Included in these studies was an assessment of where radiata pine fibre qualities fit within the spectrum of available softwood market kraft pulps, and how, and in which products they are best suited from the papermakers point of view(1). Softwood fibres are principally only used in the manufacture of printing and writing grades for their reinforcing properties. Thus, to fully assess the potential of radiata pine market kraft pulps it is necessary that their interaction with hardwood fibres, and other softwood fibre types be determined. In the present study hardwood market kraft pulps from Scandinavia (birch), mixed hardwoods (Southern USA and Korea), aspen (Eastern Canada) and eucalypt (Portugal/Spain, Thailand, Brazil and New Zealand) were assessed. For the eucalypt pulps the four geographic regions of origin gave pulps which contained 100% eucalypt pulp from different species, *E. regnans* (New Zealand), *E. globulus* (Portugal/Spain and Thailand) and *E. grandis* (Brazil). The fibre qualities and response to refining of some of these hardwood pulps, both separately and in combination with corresponding radiata pine furnishes, are described elsewhere(2).

It is generally accepted that hardwood bleached market kraft pulps can be classified into groups according to geographic origin and species composition(3)—

- Birch pulps are normally easily refined and give good wet and dry sheet strengths but poor bulk and optical properties.
- Central European and Eastern Canadian/USA pulps are comparatively moderate in strength but have good bulk and optical properties.
- USA Southern hardwood pulps are somewhat resistant to refining and have moderate strength and high bulk but poor optical properties.
- Eucalypt pulps combine the most important pulp and sheet qualities in a remarkably favourable manner. They give good wet and dry strength properties, good formation due to the short stiff fibres, and excellent bulk and optical properties.

In the present study the fibre and pulp qualities of a wide range of hardwood market kraft pulps are quantified and related to variations between and within species, geographic origins and company of manufacture.

EXPERIMENTAL

The species composition of the various pulps were determined using procedures outlined by Hughes(4). Vessel length and width measurements were made on 40 vessels per sample using a calibrated vernier scale in the microscope eye piece.

Mean fibre length (weighted by length) and relative fibre coarseness values were determined using a Kajaani FS 200 instrument.

For cross-section fibre dimension measurements, pulp samples were dehydrated, embedded, sectioned, stained, and measurements made in accordance with procedures described in detail elsewhere(5). Fibre width, thickness, and wall area are as indicated in Figure 1. The product fibre width by fibre thickness represents the minimum area fibre cross-section rectangle and can indicate overall changes in fibre cross-section dimensions. Also, fibre cross-section wall area is representative of the fibre wall volume per unit length. Wall thickness can be less meaningful than wall area (as a measure of fibre coarseness) since a decrease in the width by thickness product will cause wall thickness to increase and wall area to remain unchanged(6). The ratio width:thickness can give

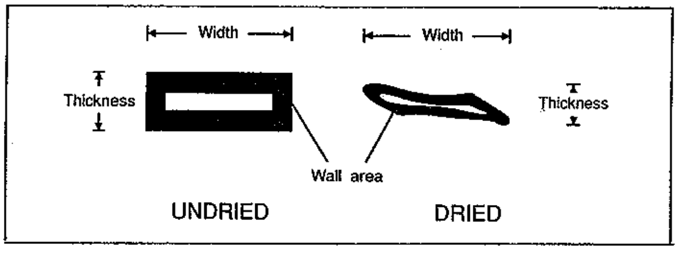

Fig. 1 — Cross-section dimension determinants for undried, and dried and rewetted fibres.

an indication of fibre collapse since the greater the width and lower the thickness of a fibre cross-section, the greater is the extent of fibre collapse. Finally Figure 1 shows that during drying fibre cross-sections and fibre walls collapse and contract(2,6). Also, fibre cross-section shapes change with drying so that the width dimension reflects different fibre configurations for undried and dried and rewetted fibres.

Pulps were reconstituted from the dry lap state (except for the undried *E. regnans*), processed in a PFI mill and made into handsheets in accordance with Appita standard procedures. Pulps were processed in a PFI mill at 10% stock concentration with an applied load of 1.8 N/mm.

The *E. regnans* 'bleached market kraft pulp' from New Zealand was made from a 20 year old tree of chip basic density about 413 kg/m^3 at the Technology laboratory of NZFP Pulp and Paper Ltd. The pulp was made to an average Kappa number of 15.7 using a chemical charge of 12.4% active alkali, sulfidity 30%, liquor:wood ratio 4:1, maximum temperature 176 °C, and H factor 1000. Bleaching conditions for the sequence C/DE/HD were: C/D charge 0.2 chlorine multiple, sequential replacement 30% chlorine dioxide, ambient temperature, time 45 min, and s.c. 3%; E/H charge 1.6% NaOH, 1.0% hypochlorite, temperature 50 °C, time 90 min, and s.c. 10%; D charge 0.9% chlorine dioxide, buffer 0.4% NaOH, temperature 70 °C, time 180 min and s.c. 10%.

The *E. regnans* pulp was used in both the undried and dried and rewetted state. The undried pulp was formed on a CTP formette, then dried under restraint on a plate dryer at 90 °C. The grammage of the lap pulp was roughly equivalent to that of the eucalypt market pulps(2). The *E. regnans* 'bleached market kraft' is a laboratory prepared pulp made from one tree; it may not exhibit all the properties of a true bleached market kraft pulp.

RESULTS AND DISCUSSION

Compositions of pulps

Compositions for the eucalypt, birch, mixed hardwood and aspen pulps are listed with geographic region of origin in Table 1. All the eucalypt pulps contain fibres, vessels and other cell material of eucalypt origin only. These pulps originate from Brazil (*E. grandis*), Portugal/Spain and Thailand (*E. globulus*), and New Zealand (*E. regnans*). The eight birch pulps, on the other hand, while all originating from Scandinavia have birch contents ranging from 30 to 96%. Other species included in the pulps are beech, aspen/poplar, spruce, pine, and alder in various proportions. The aspen pulp was from Eastern Canada and contained 90% aspen/poplar fibre and 10% spruce and jack pine. Of the four mixed hardwood pulps three were from Southern USA and one from Korea. Actual compositions are highly variable, as expected (Table 1).

Vessel dimensions

Compared with birch, aspen and mixed hardwoods eucalypt vessels are short and wide; the length:width ratios are very low and width by thickness areas are roughly the same or slightly higher.

Gross differences in compositions and dimensions are evident from the photomicrographs of Figures 2 and 3. The three eucalypts *E. regnans*, *E. globulus* and *E. grandis* appear roughly similar as do their vessel dimensions. In contrast, birch, aspen and mixed hardwoods appear very different from those of the eucalypts as well as from one another. Main differences are in vessel shape and size and the very high proportion of short, particulate non-fibrous cellular material in the mixed hardwoods.

Table 1
Dimensions of intact vessels and species composition

General description	Geopgraphic origin	Species composition %	Length width dimensions* Length mm	Width mm	Length × width range mm^2	Length: width	Length × width mm^2
E. regnans	New Zealand	Eucalypt (100)	0.38	0.18	0.69 – 0.14 × 0.31 – 0.04	2.1	0.068
E. globulus	Portugal/Spain/Thailand	Eucalypt (100)	0.41	0.18	0.61 – 0.25 × 0.31 – 0.04	2.3	0.074
E. globulus			0.45	0.19	0.70 – 0.16 × 0.30 – 0.08	2.4	0.086
E. globulus[1]			0.33	0.14	0.65 – 0.12 × 0.22 – 0.04	2.4	0.045
E. globulus			0.36	0.16	0.65 – 0.16 × 0.30 – 0.07	2.2	0.057
E. globulus			0.36	0.14	0.53 – 0.17 × 0.26 – 0.05	2.6	0.054
E. globulus			0.37	0.15	0.59 – 0.24 × 0.25 – 0.08	2.5	0.056
E. globulus			0.47	0.14	0.88 – 0.25 × 0.22 – 0.05	3.4	0.067
E. grandis[1]	Brazil	Eucalypt (100)	0.36	0.15	0.70 – 0.16 × 0.46 – 0.05	2.4	0.065
E. grandis[2]			0.44	0.16	0.82 – 0.16 × 0.28 – 0.04	2.7	0.075
Birch	Scandinavia	Birch (83) Poplar/Aspen (9) Spruce (5) Pine (3)	0.65	0.08	0.88 – 0.32 × 0.13 – 0.04	8.1	0.052
Birch		Birch (83) Poplar/Aspen (12) Alder (4) Spruce (1)	0.69	0.08	1.05 – 0.26 × 0.13 – 0.04	8.6	0.058
Birch		Birch (76) Poplar/Aspen (11) Beech (3) Alder (2) Spruce (3) Pine (5)	0.54	0.08	0.95 – 0.24 × 0.12 – 0.04	6.7	0.044
Birch		Birch (70) Poplar/Aspen (11) Beech (8) Alder (3) Other (1) Pine (7)	0.67	0.08	1.09 – 0.25 × 0.12 – 0.04	8.4	0.055
Birch		Birch (86) Poplar/Aspen (14)	0.66	0.09	1.12 – 0.26 × 0.17 – 0.04	7.3	0.059
Birch		Beech (60) Birch (30) Poplar/Aspen (5) Other (2) Spruce (2) Pine (1)	0.51	0.08	0.83 – 0.21 × 0.13 – 0.04	6.4	0.041
Birch		Birch (80) Poplar/Aspen (8) Beech (3) Alder (3) Spruce (4) Pine (2)	0.59	0.07	1.04 – 0.22 × 0.16 – 0.04	8.4	0.043
Birch		Birch (96) Poplar/Aspen (1) Spruce (2) Pine (1)	0.70	0.08	1.08 – 0.38 × 0.12 – 0.04	8.7	0.061
Aspen	Eastern Canada	Poplar/Aspen (90) Spruce (4) Pine (6)	0.60	0.08	0.89 – 0.33 × 0.13 – 0.03	7.5	0.048
Mixed hardwood	Southern USA/Korea	Liquidamber (38) Sycamore (26) Oak (8) Poplar/Aspen (11) Buckeye (8) Tuliptree (4) Tupelo (5)	0.70	0.10	1.59 – 0.17 × 0.42 – 0.05	7.0	0.062
Mixed hardwood		Oak (28) Liquidamber (16) Tupelo (14) Maple (11) Hickory (11) Poplar/Aspen (10) Tuliptree (9) Magnolia (1)	0.74	0.08	1.80 – 0.23 × 0.18 – 0.04	9.2	0.059
Mixed hardwood		Liquidamber (42) Sycamore (19) Tuliptree (18) Oak (7) Poplar/Aspen (4) Maple (3) Buckeye (5) Other (2)	0.69	0.09	1.41 – 0.24 × 0.20 – 0.04	7.7	0.060
Mixed hardwood		Tupelo (28) Liquidamber (15) Tuliptree (4) Birch (16) Oak (13) Cherry (9) Poplar/Aspen/Willow (9) Beech (6)	0.58	0.09	1.26 – 0.21 × 0.30 – 0.04	6.4	0.052

* Eucalypt pulps — For many of the vessels measured the ligule represented more than half of the length measured. Thus, length values for the eucalypt vessels as well as overall vessel areas are high relative to those of the other furnishes analysed.

Fibre dimensions

Mean fibre lengths (weighted by length) are lowest for the eucalypts and generally highest for the mixed hardwoods (Table 2). Based on mean fibre length values, differences between the birch, aspen and mixed hardwoods are small, if present at all. When overall fibre length population distributions are considered, on the other hand, those for the mixed hardwoods are broader than either aspen or birch which are roughly similar, although the tail of the aspen fibre distribution is exceptionally long reflecting a softwood presence (Fig. 4, Table 1). The high proportion of short material in the mixed hardwoods is explained by the presence of high proportions of small particulate cellular material (Fig. 4). The fibre length distribution for the eucalypts is very narrow and uniform when compared with those of either the birch or the mixed hardwoods. Of the eucalypts, *E. globulus[1]* has a low mean fibre length and contains a high proportion of short particulate material (Fig. 5,6). With the exception of the *E. globulus[1]* furnish, all the other eucalypts have similar mean fibre lengths (Table 2) and length population distributions (unpublished data). It should be noted that while all pulps contain some short material and debris, much of this material is not detected with the Kajaani FS 200 instrument (Fig. 4,5) (unpublished data).

The fibre width by fibre thickness product reflects fibre cross-section size and overall shape (2,6). Thus fibre width by thickness products for the eucalypts are generally small and show the eucalypt fibres to be more slender than either the birch, aspen or mixed hardwood fibres (Table 2). Considerable variation occurs with the mean width by thickness products within each of the eucalypt, birch, and mixed hardwood series (Table 2). Differences between the pulps become more obvious when width by thickness product population distributions are examined (Table 3). Based on these data the eucalypts are divided into three groups: *E. regnans, E. globulus/E. grandis[A]*, and *E. globulus/E. grandis[B]* (Table 2). Based on fibre width by thickness product values, similar population distributions are obtained for *E. regnans* and the *E. globulus/E. grandis[A]* relationships. Thus, for the ten eucalypt pulps, definite differences in fibre width by thickness products (a measure of fibre slenderness) occur both within and between species. For the birch, aspen and mixed hardwoods, fibre width by thickness product population distributions are roughly similar, but with the birch containing few very wide fibres compared with the aspen and mixed hardwoods. (Fig. 8).

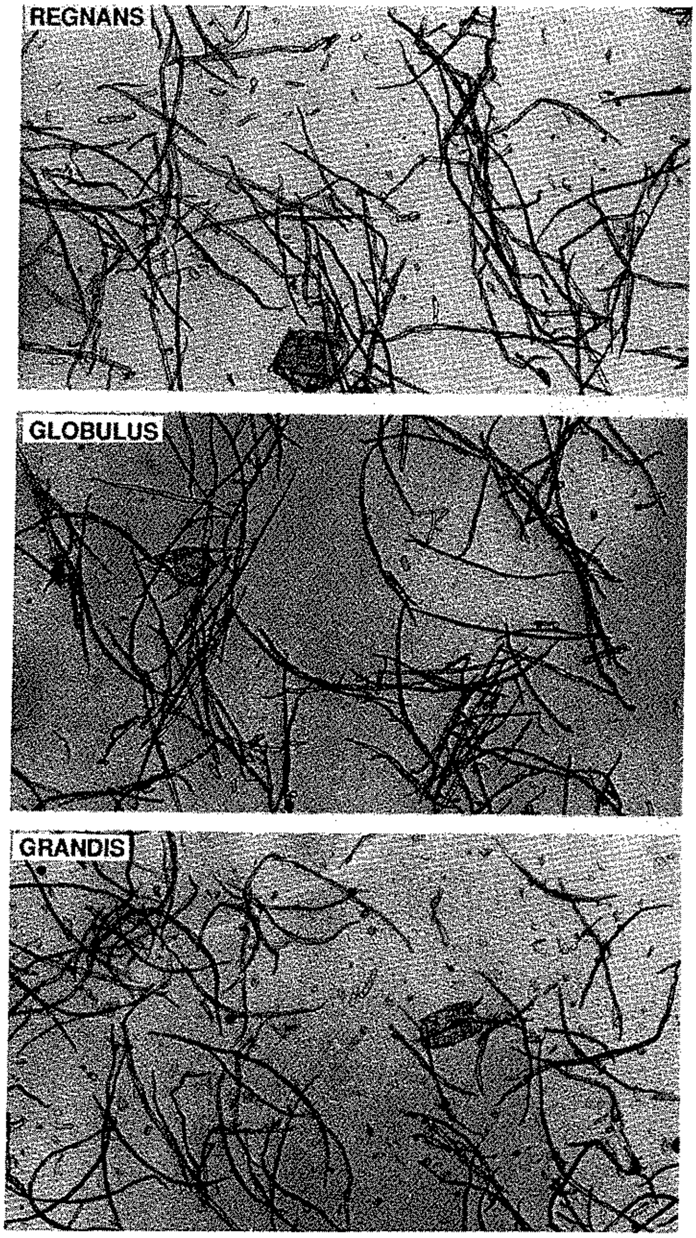

Fig. 2 — Fibre, vessel and particulate material in three eucalypt pulps.

Table 2
Fibre length and cross-section dimensions

General description	Origin	Grouping	Fibre length mm	Width µm	Thickness µm	Width × thickness µm²	Wall area µm²	Wall thickness µm	Width: thickness	Relative number of fibres per unit mass
				Fibre cross-section dimensions						
E. regnans	New Zealand	*E. regnans*	0.75	15.6	6.0	95	58	1.98	2.73	100
E. globulus	Portugal/Spain/ Thailand	*E. globulus/E. grandis [A]*	0.75	12.8	6.9	90	58	2.21	1.93	100
E. globulus			0.70	14.3	6.2	89	61	2.39	2.44	102
E. globulus[1]			0.58	13.6	6.6	90	62	2.58	2.24	121
E. globulus			0.71	13.7	7.3	101	64	2.26	2.02	96
E. globulus		*E. globulus/E. grandis [B]*	0.73	14.0	7.1	100	68	2.62	2.07	88
E. globulus			0.67	14.9	7.0	106	71	2.56	2.24	91
E. globulus			0.74	13.7	7.8	107	76	2.96	1.87	77
E. grandis[1]	Brazil	*E. globulus/E. grandis [A]*	0.72	13.4	6.6	90	62	2.53	2.12	97
E. grandis[2]		*E. globulus/E. grandis [B]*	0.72	16.0	7.0	113	77	2.77	2.43	78
Birch	Scandinavia	Birch	0.80	16.7	6.6	110	73	2.40	2.71	74
Birch			0.85	16.1	7.4	122	77	2.33	2.25	66
Birch			0.81	17.2	8.1	144	87	2.34	2.27	62
Birch			0.85	17.5	7.6	138	90	2.57	2.38	57
Birch			0.84	17.2	8.3	145	97	2.81	2.17	53
Birch			0.77	17.0	8.2	141	97	3.02	2.16	58
Birch			0.85	17.8	7.9	143	94	2.69	2.36	54
Birch			0.91	18.6	8.4	161	106	2.86	2.29	45
Aspen	Eastern Canada	Aspen	0.88	17.6	8.0	147	95	2.64	2.37	52
Mixed hardwood	Southern USA/Korea	Mixed hardwood	0.87	15.8	8.1	130	85	2.68	2.11	59
Mixed hardwood			0.97	16.2	7.5	125	86	2.94	2.33	52
Mixed hardwood			0.97	16.3	8.5	142	97	3.03	2.09	46
Mixed hardwood			0.85	15.9	8.6	142	91	2.65	1.95	56
	LSD*			1.0	0.4	11	7	0.15	0.17	

* Least significant difference between means at the 95% level of significance.

Compared with the distributions of the eucalypts, the birch, aspen and mixed hardwoods are generally broader and contain more wide and wider fibres (Fig. 8). Finally, *E. regnans* and *E. globulus/E. grandis[B]* width by thickness products represent the extremes obtained with the ten eucalypt pulps (Fig. 7), and these values are consistently smaller and population distributions are substantially narrower and uniform than those of the birch, aspen and mixed hardwoods (Fig. 8).

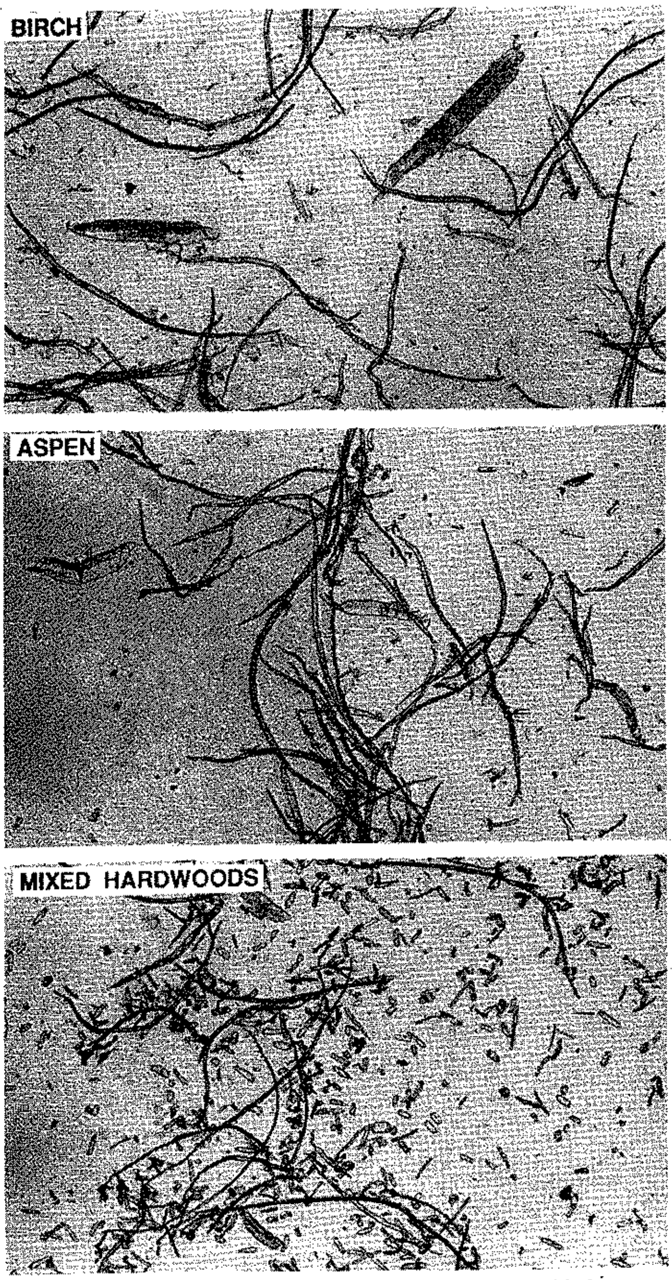

Fig. 3 — Fibre, vessel and particulate material present in birch, aspen and mixed hardwood pulps.

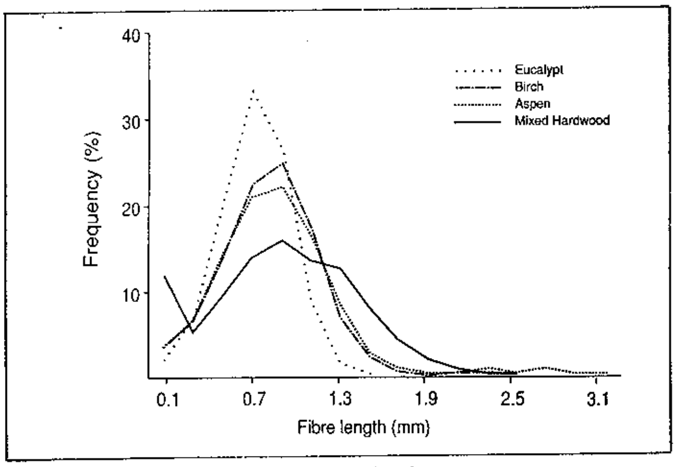

Fig. 4 — Fibre length population distributions.

Fibre cross-section wall area is equivalent to fibre wall volume per unit length of fibre and is considered a fundamental measure of fibre coarseness(7). With few exceptions the ten eucalypt pulps contain fibres with mean cross-section wall areas less than those of the aspen, birch and mixed hardwood pulps (Table 2). Again the eucalypts are separated into three groups *E. regnans*, *E. globulus/E. grandis[A]* and *E. globulus/E. grandis[B]* (Table 2). The *E. regnans* and *E. globulus/E. grandis[A]* fibre wall area population distribution curves are roughly similar but very different from those of the *E. globulus/E. grandis[B]* series (Fig. 9, Table 4). The *E. globulus/E. grandis[A]* and *E. regnans* fibre populations contain high proportions of fibres

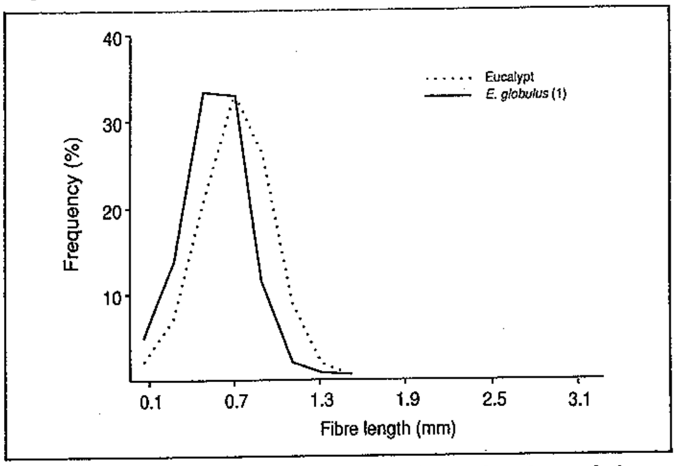

Fig. 5 — *Eucalyptus spp* and *E. globulus[1]* fibre length population distributions.

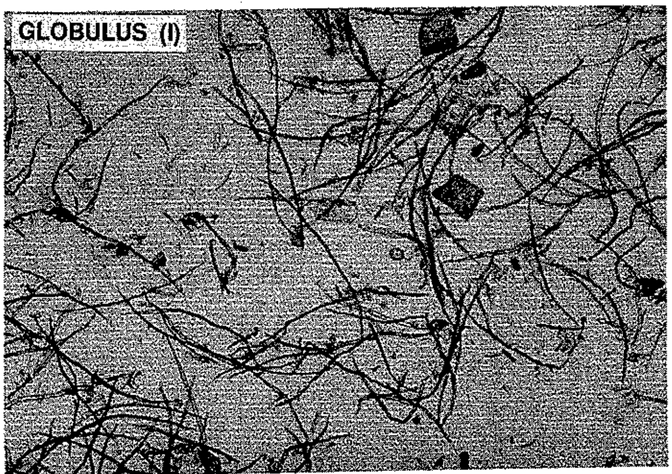

Fig. 6 — Fibre, vessel and particulate material present in *E. globulus [1]* pulp relative to *E. grandis* and *E. regnans* pulps.

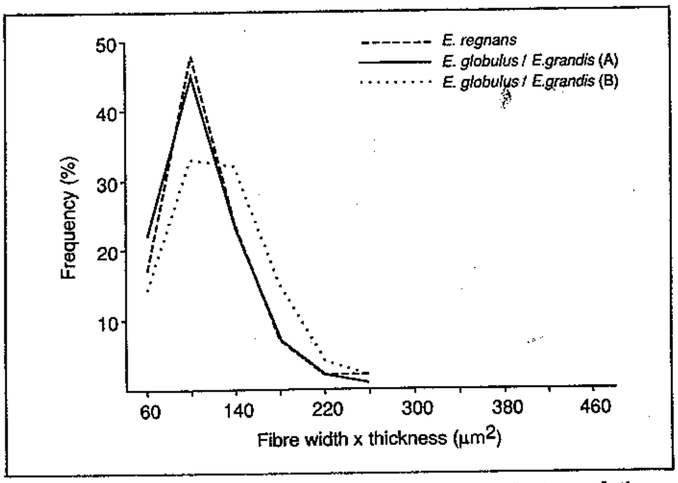

Fig. 7 — Eucalypt fibre width by fibre thickness product population distributions.

with low wall areas and are highly uniform with narrow distribution ranges compared with corresponding *E. globulus/E. grandis[B]* populations. The birch, aspen and mixed hardwoods have similar population distributions with the aspen containing the greatest number of fibres with high wall area values (Fig. 10). When compared with the extreme eucalypts, *E. regnans* and *E. globulus/E. grandis[B]*, fibre wall area population distributions for the birch, aspen and mixed hardwoods are broader, less uniform and contain high proportions of fibres with high wall areas. A significant proportion of the fibres in these pulps have wall areas which are greater than any of those of the eucalypts (Fig. 10). In summary, therefore, the ten eucalypts show a wide range of fibre wall area values. The eucalypts, however, are overall of smaller fibre wall area and populations are considerably more uniform than those of the birch, aspen and mixed hardwood pulps.

Mention needs to be made of other properties listed in Table 2; wall thickness, fibre width:thickness ratio, and relative number of fibres per unit mass. Firstly, wall thickness is not necessarily a measure of fibre coarseness since wall thickness is related to both the width by thickness product or slenderness of a fibre and the cross-section wall area or wall volume per unit length(2,6,7). Relative number of fibres per unit mass is based on a value of 100 for *E. regnans*. Note that overall numbers of fibres per unit mass decrease through the ten eucalypts as fibre cross-section wall areas increase and mean fibre lengths remain essentially unchanged. The very high value of 121 fibres per unit mass for *E. globulus[1]* is primarily related to its very short fibre length. The relative number of fibres per unit mass is much higher for the eucalypts compared with birch, mixed hardwood or aspen. This is related to the longer mean lengths and the generally higher cross-section wall areas of the birch, aspen and mixed hardwood fibres.

Handsheet properties

Handsheet physical evaluation data for the range of pulps examined are listed in Table 5. Note that only the *E. regnans* pulp was evaluated for both undried, and dried and rewetted pulp. All other pulps were reconstituted from the dry lap market pulp state. For given handsheet apparent densities, the *E. regnans* and birch developed the lowest tensile strength and the mixed hardwood and *E. globulus* pulps the highest (Fig. 11). However, the development of tensile strength and apparent density with refining can be limited, particularly for the mixed hardwood pulps. Thus for a given refining input, tensile strength development is highest for the *E. regnans* and some birch pulps (Table 5). Also, tensile strength development with refining is very high and very rapid for the undried *E. regnans*; even the unrefined undried *E. regnans* has extremely high tensile strength and apparent density (Table 5). Thus, this pulp when used in the undried

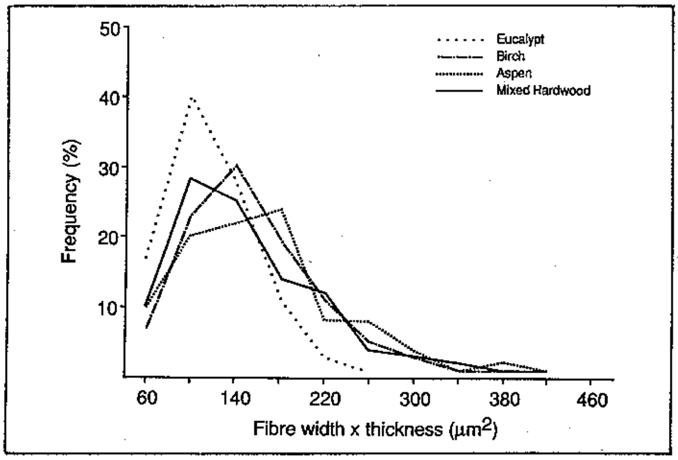

Fig. 8 — Eucalypt, birch, aspen and mixed hardwood fibre width by fibre thickness product population distributions.

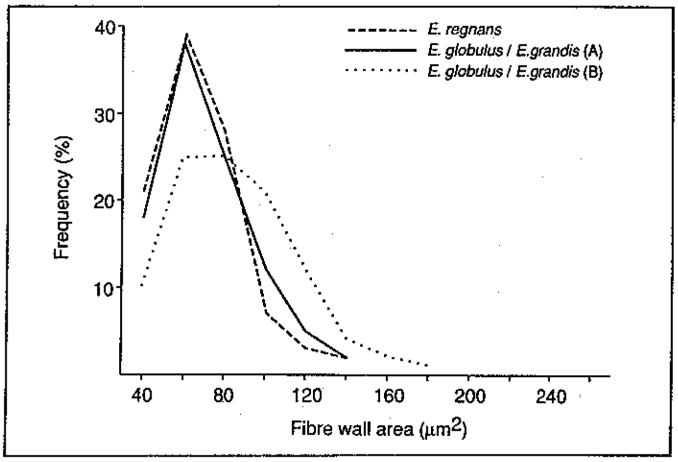

Fig. 9 — Eucalypt fibre wall area population distributions.

Table 3
Fibre width × fibre thickness product population distributions — Frequency, %

Pulp	Fibre width × Fibre thickness classes, μm^2												
	<60	100	140	180	220	260	300	340	380	420	460	500	540
E. regnans	17	48	24	7	2	2							
E. globulus/	21	47	23	7	2								
E. grandis [A]	23	47	22	5	2	1							
	23*	47	22	5	2	1							
	23†	47	22	6	1	1							
	19	37	25	12	6	1							
Mean	22	45	23	7	2	1							
E. globulus/	13	33	31	19	3	1							
E. grandis [B]	14	39	27	14	3	2	1						
	15	39	33	10	2	1							
	14‡	29	34	15	6	2							
Mean	14	35	31	15	4	1							
Birch	5	23	26	22	14	4	2	2	1	1			
	4	20	33	23	12	3	2	2	1				
	11	26	33	15	10	4		1					
	12	18	29	14	10	9	4	2	2				
	6	22	34	16	10	8	3	1					
	2	17	27	23	15	5	5	3	1	1	1		
	6	23	25	21	12	8	3	1	1				
	12	33	34	16	2	2	1						
Mean	7	23	30	19	11	5	3	1	1				
Mixed hardwoods	7	28	29	17	12	3	2	1	1				
	10	30	20	12	13	5	5	3	2				
	12	29	29	14	8	2	3	1	1	1			
	10	25	21	15	15	7	3	1	2	1			
Mean	10	28	25	14	12	4	3	2	1	1			
Aspen	10	20	22	24	8	8	4	1	2	1			

* *E. grandis[1]*
† *E. globulus[1]*
‡ *E. grandis[2]*

(slush) state should require minimal or no refining to develop desired properties.

Light scattering coefficients at given handsheet apparent densities are similar for the birch, *E. globulus* and *E. grandis* pulps. Corresponding values for the mixed hardwoods are lower, and those of *E. regnans* considerably higher (Fig. 12). Again the *E. regnans* pulp must be dried and rewetted for realistic apparent density and light scattering coefficient values to be attained. When compared at given tensile strengths, handsheet light scattering coefficients are greatest

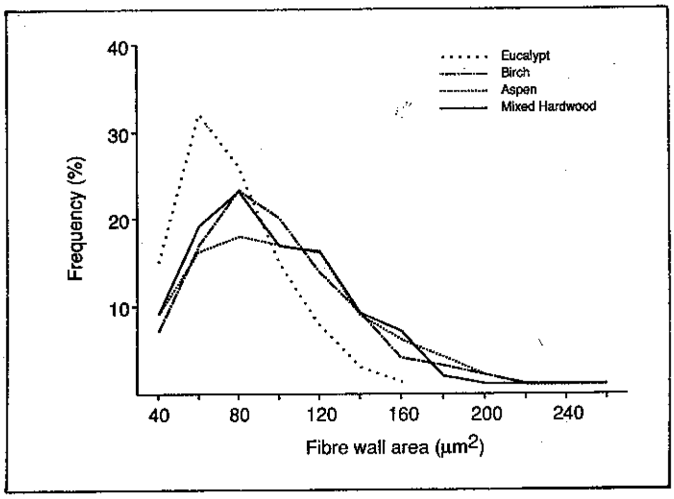

Fig. 10 — Eucalypt, birch, aspen and mixed hardwood fibre wall area population distributions.

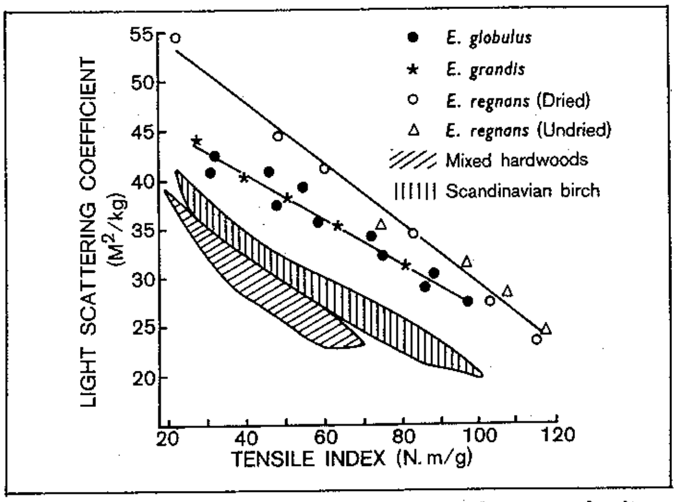

Fig. 12 — Handsheet light scattering coefficient and apparent density.

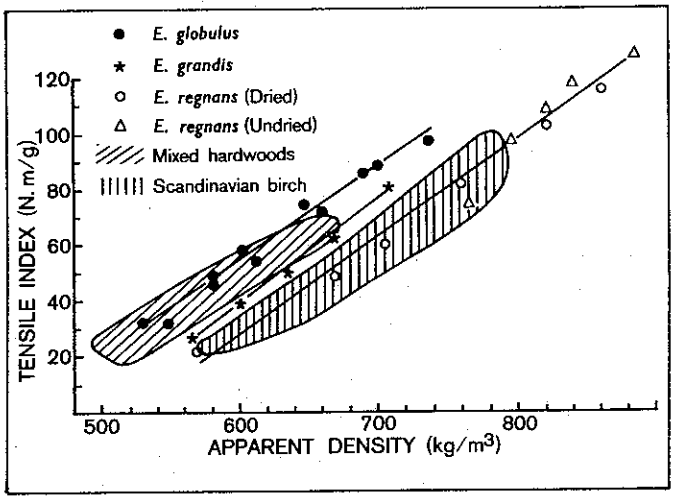

Fig. 11 — Handsheet tensile index and apparent density.

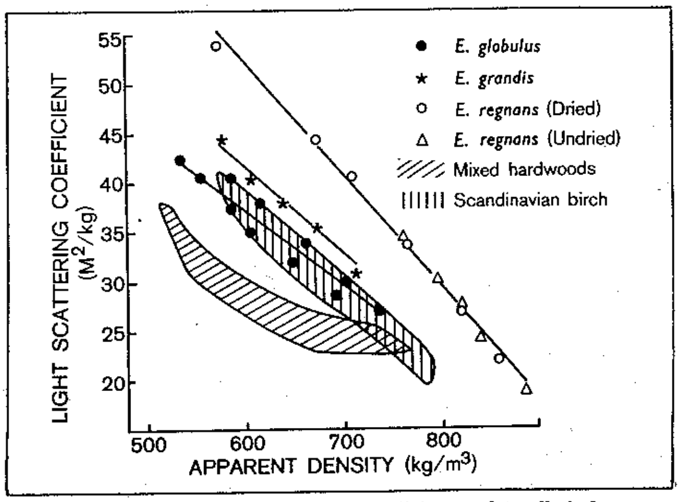

Fig. 13 — Handsheet light scattering coefficient and tensile index.

Table 4
Fibre wall area population distributions — Frequency, %

Pulp	Fibre wall area classes, μm²											
	40	60	80	100	120	140	160	180	200	220	240	260
E. regnans	21	39	28	7	3	2						
E. globulus/	18	38	27	11	4	2						
E. grandis [A]	17	35	30	10	6	2						
	15*	42	23	14	3	3						
	22†	30	22	15	9	2						
	20	40	25	11	2	2						
Mean	18	38	25	12	5	2						
E. globulus/	9	23	27	22	13	4	2					
E. grandis [B]	9	32	29	15	9	4	2					
	13	28	30	17	10	2						
	9‡	24	23	23	13	4	2	2				
Mean	10	27	27	19	11	4	2					
Birch	4	13	20	23	19	12	4	3	2			
	12	20	27	21	10	7	2	1				
	3	11	22	21	24	8	6	2	2	1		
	9	23	38	16	9	2	1	1	1			
	13	18	22	16	8	11	4	6	1	1		
	6	18	22	22	12	9	5	4	2			
	2	12	15	21	22	9	6	4	5	2	2	
	5	19	15	24	13	12	6	3	2	1		
Mean	7	17	23	20	14	9	4	3	2	1		
Mixed	6	19	27	22	9	10	4	1	1	1		
hardwoods	8	17	21	15	11	8	9	3	4	1	2	1
	10	22	23	18	8	6	7	3	1	1	1	1
	11	18	21	13	12	12	6	1	1	2	2	1
Mean	9	19	23	17	10	9	7	2	1	1	1	1
Aspen	9	16	18	17	16	9	6	4	2	1	1	1

* *E. grandis[1]*
† *E. globulus[1]*
‡ *E. grandis[2]*

for *E. regnans* and least for the mixed hardwoods (Fig. 13). The interesting feature is the very high light scattering coefficient of the dried and rewetted *E. regnans* compared with all other pulps. The dried and rewetted *E. regnans* appears to have unique optical characteristics at both given apparent densities and tensile indices. Also, this pulp requires less refining to develop or retain these optical properties. However, the *E. regnans* develops tensile strengths at higher apparent densities than do either *E. globulus* or *E. grandis*. Tensile strength development with apparent density for the *E. regnans* pulp is, however, essentially identical to that of conventional birch furnishes.

CONCLUSIONS

The fibres of eucalypt pulps made from *E. regnans*, *E. globulus* and *E. grandis* are slender with low width by thickness products, short, generally of low coarseness or fibre wall volume per unit length, and contain considerably more fibres per unit mass than do corresponding birch, mixed hardwood or aspen pulps. Fibre qualities of the ten eucalypts studied vary greatly depending on their origin or company of manufacture. The seven *E. globulus* pulps can be divided into two groups depending on fibre quality although they all originate from the Spain/Portugal area except for one from Thailand. Included in each of these groups is one of

Table 5
Handsheet physical evaluation data

Market kraft pulp	PFI mill rev	Freeness CSF	Apparent density g/cm³	Burst index kPa.m²/g	Tear index mN.m²/g	Tensile index N.m/g	Air resistance S/100 mL	Light scattering coefficient m²/kg
E. regnans	0	398	0.763	4.8	10.8	74	29	34.8
(undried)	500	416	0.794	6.9	10.2	97	50	31.2
	1000	360	0.820	8.2	9.4	108	106	27.8
	2000	299	0.840	9.3	8.9	118	204	24.1
	4000	204	0.885	10.9	8.4	128	1211	18.8
	6000	160	0.909	11.2	7.8	129	1800	15.9
E. regnans	0	530	0.565	0.9	3.7	22	3	54.6
(dried)	500	457	0.667	2.7	10.5	48	11	44.3
	1000	424	0.704	3.4	10.9	60	16	40.6
	2000	337	0.758	5.6	10.3	83	41	34.4
	4000	250	0.820	7.5	9.9	103	133	27.4
	6000	166	0.862	9.2	9.3	116	572	22.6
E. globulus	0	409	0.549	1.2	3.6	31	2	40.6
(dried)	500	447	0.578	2.2	7.2	46	2	40.6
	1000	429	0.610	2.9	6.7	54	4	38.0
	2000	338	0.658	4.2	8.5	72	9	34.2
	4000	237	0.699	5.6	8.7	88	29	30.6
	6000	159	0.735	6.8	8.5	97	105	27.2
E. globulus	0	408	0.529	1.3	4.1	31	1	42.5
(dried)	500	399	0.578	2.6	6.5	48	2	37.1
	1000	355	0.599	3.2	7.5	58	3	35.4
	2000	314	0.645	4.5	8.7	75	6	31.9
	4000	239	0.690	6.0	9.5	86	21	28.5
E. grandis	0	405	0.565	1.2	5.1	27	3	44.3
(dried)	500	431	0.599	2.0	7.3	39	4	40.3
	1000	391	0.633	2.9	9.3	50	8	38.1
	2000	351	0.667	3.8	11.3	63	13	35.3
	4000	276	0.709	5.6	10.2	81	28	30.8
Birch	0	519	0.602	0.9	4.1	25	2	36.8
(dried)	500	568	0.654	2.3	7.1	45	2	31.5
	1000	541	0.676	2.8	7.9	53	3	29.2
	2000	457	0.714	4.1	7.6	69	7	27.1
	4000	346	0.763	5.7	7.1	86	26	23.7
Birch	0	436	0.629	1.5	6.0	33	2	35.4
(dried)	500	443	0.685	2.8	7.6	51	4	30.0
	1000	429	0.714	3.5	8.0	63	6	27.7
	2000	395	0.752	4.9	8.0	79	13	24.4
	4000	255	0.787	5.9	7.7	91	46	20.9
Birch	0	515	0.581	1.2	6.4	28	2	37.7
(dried)	500	555	0.621	2.1	7.9	41	3	33.3
	1000	524	0.654	2.8	8.5	53	4	30.3
	2000	453	0.690	3.9	8.4	67	7	27.1
	4000	380	0.719	4.5	8.4	76	20	24.9
Birch	0	515	0.568	0.8	4.3	22	1	41.1
(dried)	500	543	0.633	1.7	6.2	36	2	36.1
	1000	406	0.667	2.4	7.3	45	4	33.3
	2000	422	0.714	3.5	6.8	60	8	29.0
	4000	329	0.763	4.7	6.1	75	27	24.5
Birch	0	419	0.649	2.3	6.1	47	3	31.2
(dried)	500	431	0.690	3.4	7.9	64	6	28.9
	1000	378	0.719	4.8	7.6	79	8	24.9
	2000	289	0.752	5.7	8.1	92	22	22.3
	4000	186	0.781	6.8	7.2	100	87	19.5
Birch	0	447	0.629	1.5	4.5	33	3	34.4
(dried)	500	481	0.667	2.7	7.1	50	4	29.8
	1000	454	0.685	3.4	8.0	59	6	27.3
	2000	378	0.735	4.1	8.6	79	14	24.3
	4000	293	0.781	5.9	8.0	93	47	20.9
Birch	0	482	0.653	1.7	5.3	35	4	34.1
(dried)	500	505	0.699	2.8	7.8	52	6	29.5
	1000	474	0.714	3.8	8.1	63	9	27.2
	2000	434	0.746	4.8	8.1	67	16	24.3
	4000	335	0.787	6.0	8.1	86	52	20.9
Mixed hardwood	0	550	0.556	1.3	8.8	29	1	31.6
(dried)	500	600	0.585	2.1	12.0	41	2	28.9
	1000	527	0.602	2.8	10.8	47	2	26.5
	2000	477	0.633	3.6	10.4	57	4	25.1
	4000	336	0.667	4.6	9.7	70	12	22.8
Mixed hardwood	0	524	0.508	0.7	3.9	18	1	38.0
(dried)	500	543	0.541	1.3	5.2	27	1	34.8
	1000	502	0.559	1.7	7.0	35	1	32.9
	2000	449	0.595	2.5	7.3	46	2	30.5
	4000	338	0.645	3.8	8.2	59	7	27.3
Mixed hardwood	0	581	0.493	1.1	6.0	25	1	
(dried)	500	575	0.535	1.9	8.9	36	1	31.5
	1000	518	0.571	2.6	7.8	45	2	29.2
	2000	449	0.588	3.1	8.3	52	3	28.1
	4000	279	0.671	4.3	8.5	66	11	24.7

the two *E. grandis* pulps from Brazil. Similar variabilities are shown for the eight birch and four mixed hardwoods. Despite this variability the four mixed hardwood and the eight birch pulps are of sufficiently similar fibre quality to allow grouping into birch and mixed hardwood categories.

For the eucalypts, the *E. regnans* fibres appear to have the thinnest walls, intermediate width by thickness products, and very low cross-section wall areas or wall volumes per unit length. These fibre qualities give a high width:thickness ratio, high relative number of fibres per unit mass, and unique handsheet optical properties for unrefined and lightly refined dried and rewetted *E. regnans* pulp. For given handsheet apparent densities (or bulks) and tensile indices, light scattering coefficient are extremely high for the dried and rewetted *E. regnans* pulp.

Based on handsheet properties, the mixed hardwood, *E. globulus* and *E. grandis* pulps give high tensile strengths at low apparent density (or high bulk) when compared with corresponding birch and *E. regnans* pulps. The development of tensile strength with refining is, however, very limited for the mixed hardwoods. Handsheet light scattering coefficient at given tensile indices or apparent densities are lowest for the mixed hardwoods and highest for the eucalypts with the *E. regnans* pulp having particularly excellent optical properties.

The unique and often desirable characteristics of eucalypt hardwood bleached pulps can be related to their relatively uniform fibre populations and to slender fibres with low wall volumes per unit length. These features together can give relatively thick fibre walls and high numbers of fibres per unit mass.

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