Papermaking potential of *Acacia dealbata* and *Acacia melanoxylon*

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SUMMARY

The pulping and papermaking potential of *Acacia dealbata* and *Acacia melanoxylon* were studied using *Eucalyptus globulus* as a reference. Pulp yield, alkali consumption and delignification in the kraft process, of both species, compare very well with the reference. Pulp yield can be higher than that of *E. globulus* and the residual lignin content lower after cooking, which is in good agreement with the lower lignin and extractives content of the wood samples used.

Pulps produced from Acacia have slightly lower fibre length and coarseness and higher fibre width and wet fibre flexibility than *E. globulus* pulps. As a consequence of fibre characteristics, the paper produced from Acacia is denser and exhibits higher tensile and burst strength, and lower tear resistance than that from *E. globulus*, at a given PFI revolution. For the same sheet density *E. globulus* displays higher strength properties, but the consequence of achieving this is a lower drainage rate and higher energy consumption in refining.

Key words

wood pulps, *Acacia dealbata, Acacia melanoxylon*, fibre flexibility, papermaking potential, *Eucalyptus globulus*, kraft pulps, paper properties

INTRODUCTION

Bleached *Eucalyptus globulus* kraft pulp has a strong market position for the production of writing and printing papers due to its singular characteristics. Strength, bulk, and opacity of *E. globulus* paper are very good, and smoothness acceptable. However, pulp produced from Acacia species, namely *Acacia mangium*, is emerging as a strong competitor in the world market of hardwood pulps. The increasing number of commercial plantations for industrial uses in Asia, good ecological conditions of this region (*1,2*) and fibre quality (*3,4*) are key factors promoting the use of this wood for pulp production. Very high light scattering potential of the pulp fibres, due to a high number of fibres per gram, and good smoothness and paper formation are the key parameters (*3,4*).

Table 1
Characteristics of the raw-material

Species	Provenance	Age (years)	Diameter at BH (cm)	Basic density, bottom part (g/cm3)	Basic density, top part (g/cm3)
A. dealbata	Mira- Portugal	18	16.8	0.490 (±0.010)	0.351 (±0.014)
A. melanoxylon	Camarido- Portugal	22	14.1	0.460 (±0.011)	0.387 (±0.012)

BH = Breast Height

Even though they are an introduced species in Portugal, there are good ecological conditions for some Acacia species, and there are already stands of *A. dealbata* and *A. melanoxylon*. Nonetheless, information on the papermaking potential of Acacia species existing in Portugal is scarce. Furtado (*5*) worked on the pulping potential of *A. melanoxylon* and *A. dealbata*, using a composite sample of three trees per species, with mean basic wood density of 0.530 g/cm^3 and 0.500 g/cm^3, respectively, and observed that kraft cooking yield, residual lignin content in the unbleached pulp and alkali charge required in the kraft process compare very well with those exhibited by a *E. globulus* sample used as a reference, which had a basic wood density of 0.570 g/cm^3. Similar conclusions were reported by Gil *et al* (*6*) for other trees of the same species. The pulping and papermaking potential of other Acacia species have also been studied by other researchers (*3,7,8*).

While Clark and co-workers (*7,8*) reported data for young trees, the works of Furtado (5) and Gil *et al* (*6*) concerns very old trees. However, this kind of raw material will not be available if commercial exploitation of Acacia for pulp becomes reality. So, this paper aims to study the pulping behaviour of Acacia wood younger than those used in previous studies (*5,6*). To attain this objective the material from the part of the stem above the breast height (1.30 m) was selected from the same *A. melanoxylon* and *A. dealbata* individual trees used in a previous study by Gil *et al* (*6*). The fibre characteristics, namely the wet fibre flexibility, and the papermaking potential of the bleached kraft Acacia pulps were evaluated, using *E. globulus* grown in Portugal as a reference.

Material and methods

Table 1 shows the provenance, age and density (mean and standard deviation) of the wood chips produced from the part of the stem under (bottom part) and above (top part) the breast height of two trees being studied. This work was carried out using the wood chips produced from the top part of the trees. The trees came from a sand-dune soil from two sites very close to the Atlantic Ocean.

Industrial wood chips from *E. globulus* grown in Portugal aged within the range of 8—10 years and a mean basic density of 0.536 g/cm^3 were used as reference. The three wood chip samples had been previously screened. The chip basic density was determined according to the Tappi 258 om-94 standard procedure. Representative materials were ground and samples prepared for lignin and extractives content determination according to Tappi 222 om-88 and Tappi 204 om-88 (successively with dichloremethane, ethanol and water) standards, respectively.

The wood chips were submitted to a conventional kraft cooking process under the following reaction conditions: active alkali charge - 22% (as NaOH); sulfidity index- 30%; liquor/wood ratio - 4/1; time to temperature – 90 min; time at temperature (160°C) – 120 min. Experiments were carried out with 1000-g o.d. of wood in a forced circulation digester. The cooked chips were disintegrated, washed, and screened on a L&W screen with 0.3 mm slot width.

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Table 2
Variance analysis of the different parameters, for three species (S) and four refining (R) levels.

Source	F.D.	Expected values of the average squares
Species (S)	(s-1)	$\sigma_f^2 + rf\sigma_S^2$
Refining (R)	(r-1)	$\sigma_f^2 + ef\sigma_R^2$
S x R	(s-1)(r-1)	$\sigma_f^2 + f\sigma_{SXR}^2$
Residual	(f-1)rs	σ_f^2

Where:
σ^2 – Estimated variance
e – number of species (3)
r – levels of refining (4)
f – number of handsheets (10)

The screened and total yields, kappa number and pulp viscosity were determined according to the standard methods. Residual alkali was determined in the black liquor by acid titration until pH 10.5, after appropriate dilution and $BaCl_2$ addition, in order to determine the corresponding effective alkali consumption. The morphological properties of pulp fibres were determined by image analysis of a diluted suspension in a flow chamber in Morfi®. The pulps were beaten in a PFI mill at 500, 2500 and 4500 revolutions under a refining intensity of 3.33 N/mm. Wet fibre flexibility (WFF) and relative bonded area (RBA) were determined according to Steadman and Luner (*9*) procedure, using CyberMetrics® equipment. The two parameters were measured in fibres put on slides with and without wires, respectively. Paper handsheets were prepared according to the Scan standard, and tested regarding structural, mechanical and optical properties.

The experimental data were analysed by variance analysis, using commercial software Statistics® and Statgraphics®. In the study of variance components analysis, each factor (after the first) is nested in the one above. The goal of such an analysis is usually to estimate the amount of variability contributed by each of the factors, called the variance components. The model used for variance analysis (with fixed effects) is provided in Table 2.

RESULTS AND DISCUSSION

Cooking

The basic chip density of the samples obtained from the three species under research is 0.351g/cm³, 0.387g/cm³ and 0.536g/cm³, respectively for *A. dealbata*, *A. melanoxylon* and *E. globulus*. The value for *E. globulus* is within the usual range reported for this species (*10*). The Acacia samples used in this work exhibit values that are lower than those reported in literature (0.460 to 0.530 g/cm³) for whole-trees of the same species in similar ecological conditions (*5*) but in good agreement with the data reported by Clark (*11*) for *A. melanoxylon*. The low values obtained for Acacia samples used in the present study should be analysed considering they pertain to the top part of the trees. Corresponding values for the bottom part of the trees are significantly higher (Table 1). Similar trends have been reported for the effect of height level in the tree on basic density for some hardwood and softwood species (*12-14*) and for *A. melanoxylon* (*11*).

The three samples were submitted to cooking under the reaction conditions described previously (selected in order to produce an *E. globulus* kraft pulp with kappa number in the range 14 –16, which is the usual range for this species). Table 3 presents the results for pulp yield, rejects, effective alkali consumption (as NaOH), kappa number and pulp viscosity. According to our experience with other samples cooked in the same equipment, the standard deviation of the pulp yield is close to 1 unit.

Regarding the yield, the present data show Acacia species result in higher pulp yield than the *E. globulus* sample used as a reference. Furtado (*5*), using a composite sample of three trees per species, and Gil *et al.* (*6*), using only the part of the stem under the breast height of one tree, reported similar trends for the same species. In addition, the pulp yields observed in the present study are 1-2 points lower than the corresponding yields obtained for the same trees but with the material under the breast height (*6*), which can be tentatively attributed to the increase in extractive and lignin contents with height level in the tree. The higher pulp and total yields exhibited by Acacia species are in accordance with their lower lignin and extractives content (Table 4). Despite the lower performance of this *E. globulus* wood sample regarding pulp yield, it should be noted that other *E. globulus* wood samples have pulp yields in the range of 52% to 59% (*10,15*) and also require milder cooking conditions.

Regarding kappa number, Acacia species have lower residual lignin content, for similar reaction conditions. However, this does not mean that *E. globulus* exhibits lower delignification rate than Acacia, because *E. globulus* wood has higher lignin content and the amount of lignin removed is higher.

Cooking selectivity (yield/kappa number and pulp viscosity/kappa number) is higher in the Acacia species investigated. Despite these trends, variability of the woods and their behaviour in the kraft process preclude generalisation.

The unbleached kraft pulps were submitted to a bleaching $D_0E_1D_1E_2D_2$ sequence in order to evaluate the

Table 3
Cooking results

	A. dealbata	*A. melanoxylon*	*E. globulus*
Pulp yield (%)	51.2	53.2	50.5
Rejects (%)	0.3	0.4	0.3
Alkali consumption (%)	15.6	15.1	15.2
Kappa number	12.4	10.9	14.1
Pulp viscosity (cm³/g)	996	980	956

Table 4
Lignin and extractives content

	Lignin content (%)	Extract Dichloremethane	Ethanol	Water	Total extractives
A. dealbata	18.2 (±1.16)	0.42 (±0.08)	1.91 (±0.15)	1.17 (±0.13)	3.5 (±0.08)
A. melanoxylon	17.5 (±1.59)	0.43 (±0.13)	1.81 (±0.32)	0.93 (±0.08)	3.2 (±0.41)
E. globulus	20.0 (±0.91)	1.58 (±0.03)	1.78 (±0.19)	1.37 (±0.47)	4.7 (±0.60)

Table 5
Fibre characteristics.

	Revs (PFI)	Fibre width (µm)	Length weighted in length (mm)	Coarseness (mg/m)	Curl (%)
A. dealbata	0	18.5	0.66	0.064	6.5
	500	18.2	0.67	0.060	5.2
	2500	17.8	0.66	0.064	5.3
	4500	17.7	0.67	0.063	5.4
A. melanoxylon	0	17.9	0.65	0.066	6.3
	500	17.9	0.66	0.063	5.2
	2500	17.4	0.64	0.071	5.6
	4500	17.3	0.63	0.065	5.7
E. globulus	0	16.5	0.72	0.079	5.7
	500	16.6	0.72	0.083	5.3
	2500	16.5	0.70	0.083	5.9
	4500	16.6	0.68	0.080	5.9

papermaking potential of the bleached pulp. Pulp viscosities were similar and close to 800 cm^3/g and no differences were detected regarding pulp bleachability.

Fibre properties

Table 5 shows the biometric characteristics of the fibres of the three pulps, for three refining levels and for the unrefined pulps. Regarding the unrefined pulps, the following conclusions can be drawn: (i) *E. globulus* exhibits slightly higher fibre length (0.72 mm) than *A. dealbata* and *A. melanoxylon* (0.66 mm and 0.65 mm, respectively); (ii) *E. globulus* has narrower fibres than those of *A. dealbata* and *A. melanoxylon*; (iii) *E. globulus* fibres exhibit close to 20% higher fibre coarseness than *A. dealbata* and *A. melanoxylon*. This experimental data suggests that in *E. globulus* fibres, lumens are relatively narrow and cell walls relatively thick. In accordance with their lower coarseness, Acacia species have higher number of fibres per gram of pulp; 33.4x10^6, 30.6x10^6, and 22.6x10^6 for *A. dealbata*, *A. melanoxylon*, and *E. globulus*, respectively.

Considering the higher coarseness and the lower fibre width of *E. globulus* fibres, we can anticipate fibres with lower wet fibre flexibility, and this in fact is shown in Figure 1 throughout the refining period.

It seems that wet fibre flexibility also influences initial fibre curl; *E. globulus* with higher wet fibre rigidity exhibits lower initial curl (Table 5). In addition, for the Acacia pulps, straightening of fibres with refining is obvious, when we compare values for unbeaten pulp and the corresponding pulp after 500 PFI revolutions, and this is in agreement with other authors (*16*). Fibre length increases and, consequently, coarseness apparently decreases slightly for this moderate beating level. For higher beating treatments, curl increases again.

Papermaking potential

Figure 2 presents the drainability resistance data for the three pulps, revealing that *E. globulus* is harder to refine in the initial phase, probably as a consequence of higher fibre coarseness. Unexpectedly, dewatering resistance of *E. globulus* pulp at 4500 revolutions is higher than that of Acacia species. On the other hand, *E. globulus* pulp shows, in general, lower water retention values than Acacia species throughout the refining period. Consideration of both results, suggests lower swelling and higher external fibrillation for *E. globulus* pulps. Seth (*17*), working with softwood pulps with very different coarseness, reported significantly higher external fibrillation for the coarse fibres at 6000 PFI revolutions.

The effect of refining on paper density (Fig. 3) reveals that Acacia species exhibit values about 20% higher than *E. globulus* throughout the refining period. The higher wet fibre flexibility (Fig. 1) and higher relative bonded area (Table 6) can justify these results. Even for 4500 revolutions, where drainability resistance of the *E. globulus* pulp is the highest, paper density remains significantly lower than Acacia, which is a very interesting result. This could be attributed to the different refining behaviour of the two types of fibres. The hard *E. globulus* fibres develop mainly external fibrillation, while internal fibrillation is dominant for the soft Acacia fibres.

The variance analysis (Table 7) of all the density data shows that close to 74% of the variance is attributed to refining process, while close to 25% is imputed to the species in question.

As expected from the paper density data (and corresponding paper porosity),

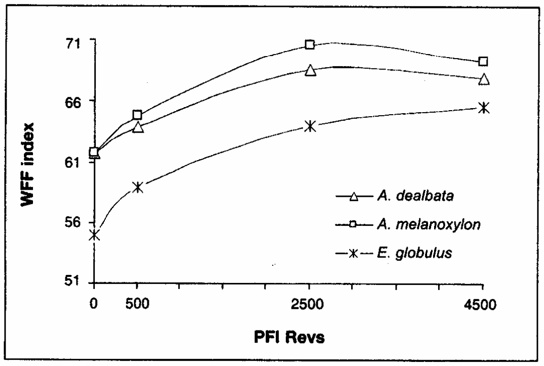

Fig. 1 **Evolution of wet fibre flexibility (WFF) index with refining, for Acacia and *E. globulus*.**

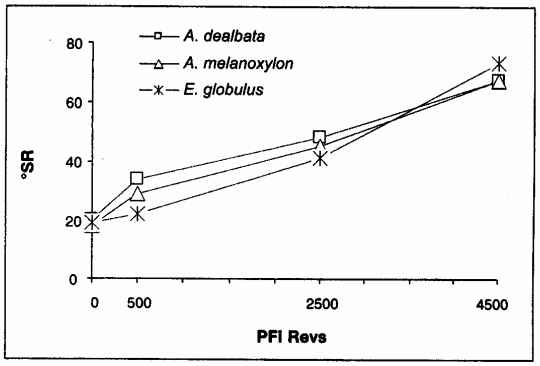

Fig. 2 **Evolution of the Schopper Riegler degree (°SR) with refining, for Acacia and *E. globulus* pulps.**

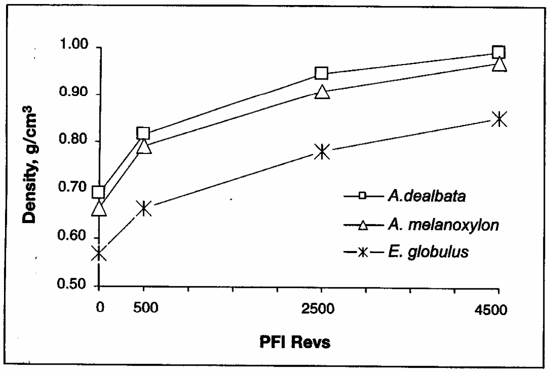

Fig. 3 Evolution of paper density with refining, for Acacia and *E. globulus* pulps.

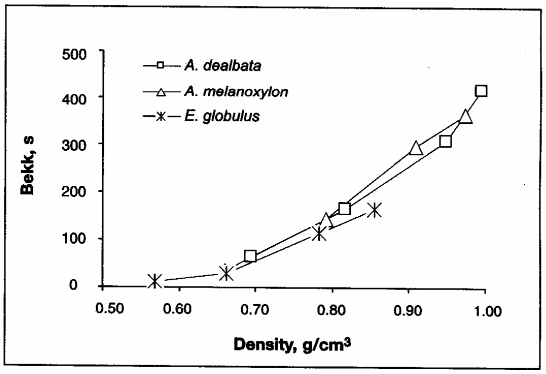

Fig. 4 Evolution of paper smoothness with paper density, for Acacia and *E. globulus*.

Table 6
Relative bonded area for Acacia and *Eucalyptus globulus* fibres

PFI, Revs	*A. dealbata*	*A. melanoxylon*	*E. globulus*
0	38.6	39.0	33.4
500	54.2	53.1	42.4
2500	76.3	67.3	60.9
4500	76.8	70.6	65.5

E. globulus exhibits higher air permeability than Acacia species at a given refining energy. Within Acacia, *A. dealbata* has a less permeable structure, which is related to the higher density (lower porosity). For similar fibre length and fibre length distribution this can in turn be explained by the higher relative bonded area (Table 6) and expected from fibre biometrics. The higher collapsibility of *A. dealbata* respecting to *A. melanoxylon* is in good agreement with the mean values of coarseness (6.3/6.8 mg/100 m) and fibre width (18.1/17.6 µm). Variance analysis of air permeability for the three species displayed the effect of refining (62%) and species (11%) as expected, but also an important interaction between these two parameters. In fact, this interaction is responsible for around 25% of total variance. In physical terms, this means that *E. globulus* and Acacia papers develop air permeability resistance in different ways during refining. In fact, while *A. dealbata* exhibits a drastic increase in air resistance between 2500 and 4500 PFI revolutions, *E. globulus* shows a much lower change for the same refining levels. These differences are in accordance with fibre morphology.

As expected, paper smoothness is higher for Acacia species, at a given refining level. A slight advantage of Acacia species remains when the comparison is made at a given paper density (Fig. 4).

Regarding mechanical properties, Acacia species exhibit higher tensile and burst strengths and lower tearing resistance than *E. globulus*, at given PFI revolutions (Fig. 5 and 6). These results are in very good agreement with the data reported by Furtado (*5*), for the same species. The results for tensile and burst are justified by the higher density and the higher internal cohesion of the papers from Acacia and the lower tearing is probably a consequence of lower fibre length and lower intrinsic fibre strength (Fig.10). Variance analysis shows tearing resistance depends on refining and species, as well as on the interaction between them. Tensile and burst are both dominated by refining (Table 7).

However, the representation of strength properties as a function of paper density (Fig. 7 and 8) and tear versus tensile (Fig. 9) reveals that *E. globulus* has potential to produce stronger papers than Acacia. The analysis of the data by Furtado (*5*), obtained for a composite wood sample of three trees per species, support the same conclusion.

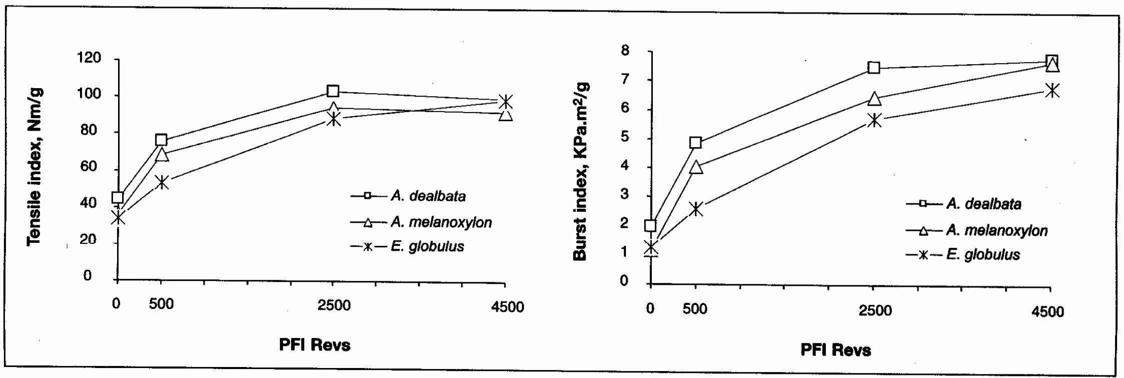

Fig. 5 Evolution of tensile index and burst index with refining, for Acacia and *Eucalyptus globulus*.

Table 7
Component variance analysis for the paper properties

Paper properties	Source	F.D.	Q.M.	Fcal	Sig.	Var (%)
Density	Species (S)	2	0.2413	2435.8	***	25.2
	Refining (R)	3	0.5309	5358.5	***	73.9
	S x R	6	0.0012	12.0	***	0.5
	Residual	108	0.0001			0.4
Resistance of air permeability	Species (S)	2	8.40E+06	240	***	11.00
	Refining (R)	3	3.54E+07	1011.8	***	62.03
	S x R	6	4.81E+06	137.47	***	25.13
	Residual	108	35018.8			1.84
Smoothness	Species (S)	2	288366	133.62	***	26.61
	Refining (R)	3	467942	216.83	***	57.74
	S x R	6	22653.3	10.5	***	7.62
	Residual	108	2158.15			8.03
Tensile Index	Species (S)	2	1564.81	99.34	***	4.52
	Refining (R)	3	23265.4	1477.01	***	90.50
	S x R	6	284.146	18.04	***	3.13
	Residual	108	15.7517			1.84
Stretch	Species (S)	2	3.89356	39.78	***	4.38
	Refining (R)	3	53.8804	550.42	***	82.69
	S x R	6	1.92252	19.64	***	8.42
	Residual	108	0.097889			4.52
Burst Index	Species (S)	2	20.7826	214.25	***	6.43
	Refining (R)	3	218.137	2248.78	***	90.32
	S x R	6	1.7414	17.95	***	2.04
	Residual	108	0.097002			1.21
Tear Index	Species (S)	2	21.387	30.18	***	8.37
	Refining (R)	3	94.725	133.66	***	50.77
	S x R	6	18.8447	26.59	***	29.38
	Residual	108	0.708704			11.48
Internal Cohesion	Species (S)	2	185635	254.62	***	7.42
	Refining (R)	3	2.16E+06	2967.35	***	86.84
	S x R	6	41013.2	56.25	***	4.85
	Residual	108	729.075			0.88
Dry zero-span strength	Species (S)	2	3083.65	82.47	***	37.95
	Refining (R)	3	2069.63	55.35	***	33.75
	S x R	6	231.473	6.19	***	9.67
	Residual	108	37.3891			18.63
Wet zero-span Strength	Species (S)	2	5393.54	128.6	***	52.94
	Refining (R)	3	1988.19	47.41	***	25.67
	S x R	6	162.923	3.88	**	4.79
	Residual	108	41.9392			16.60
Brightness	Species (S)	2	112.278	1631.64	***	13.51
	Refining (R)	3	476.432	6923.58	***	76.49
	S x R	6	20.1301	292.53	***	9.66
	Residual	108	0.068813			0.33
Opacity	Species (S)	2	60.3177	164.04	***	2.04
	Refining (R)	3	2040.52	5549.35	***	92.52
	S x R	6	36.651	99.68	***	4.94
	Residual	108	0.367705			0.50
Light Scattering coefficient	Species (S)	2	27.7677	106.26	***	0.42
	Refining (R)	3	4704.7	18004.33	***	95.55
	S x R	6	63.768	244.03	***	3.87
	Residual	108	0.261309			0.16

The results of our work can be explained by the experimental data for fibre length and zero-span tensile strength. In fact, the dry zero-span (Fig. 10) tensile strength is significantly higher in *E. globulus*. The differences are even higher (close to 12%), when the comparison is based on the corresponding wet test. Before discussing the differences among species we would like to highlight the decrease in fibre strength after wetting. The reasons for this behaviour were very well explained by Gurnagul and Page (*18*). *E. globulus*, with its high fibre-wall thickness, exhibit significantly higher fibre strength when both dry and wet. At least two characteristics could explain this superiority: (i) lower fibril angle; (ii) less weak points in the fibre wall, such as kinks and nodes. French *et al.* (*19*), comparing different *Eucalyptus* species, showed that the *E. globulus* exhibit lower fibril angle. On the other hand, Leopold and Thorpe (*20*), working with individual fibres from summer-wood and spring-wood from Norway spruce, showed that the latter (which has thin fibre walls) has much lower tensile strength. The relative importance of both mechanisms is under investigation. The variance analysis of zero-span tensile strength confirms the importance of species (Table 7). However, to produce a paper with a given density, *E. globulus* requires more energy in refining and the pulp refined to achieve this density, drains at a slower rate (Fig. 11).

Light scattering coefficient is an important characteristic of writing and printing papers. By representing light scattering as a function of paper density, figure 12 shows that light scattering is higher in Acacia, which is expected if we consider the higher specific surface of

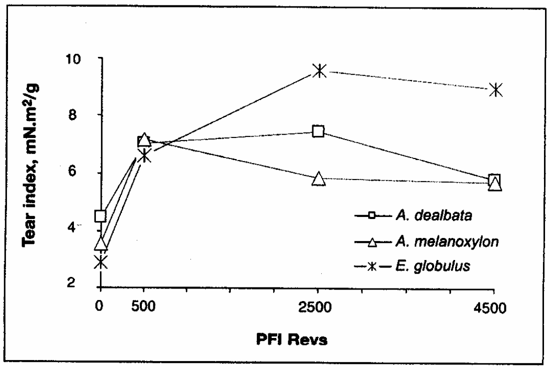

Fig. 6 Evolution of the tear index with refining, for Acacia and *E. globulus*.

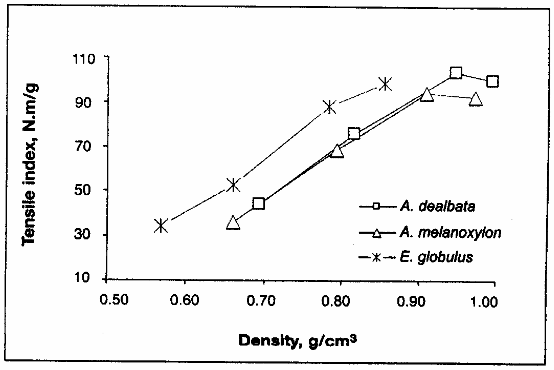

Fig. 7 Evolution of tensile index with density, for Acacia and *E. globulus*.

Acacia fibres. However, if the criterion is both light scattering and strength, and we define strength by $\sqrt{\text{Tensile Index} \times \text{Tear Index}}$, figure 13 shows that *E. globulus* compares well with Acacia, which is explained by the superior strength of *E. globulus* fibres at a given paper density (Fig. 7 and 8). Moreover, the same figures show that at given paper strength, *E. globulus* produces bulkier handsheets than Acacia. According to the theory of bending stiffness, it is expected that *E. globulus* handsheets are stiffer than Acacia, which is an important end-use property. On the contrary, paper smoothness of *E. globulus* is lower at a given strength.

CONCLUSIONS

The Acacia species studied (*A. dealbata* and *A. melanoxylon*) exhibit slightly better performance in pulping than the *E. globulus* sample used as a comparison. Pulp and total yields are 1-2 points higher; alkali consumption is similar and residual lignin content lower, constituting an advantage in the bleaching process.

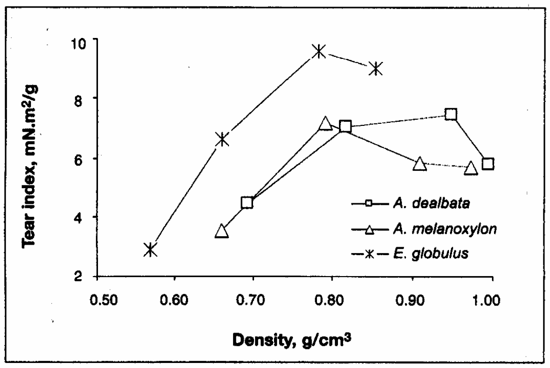

Fig. 8 Evolution of tear index with density, for Acacia and *E. globulus*.

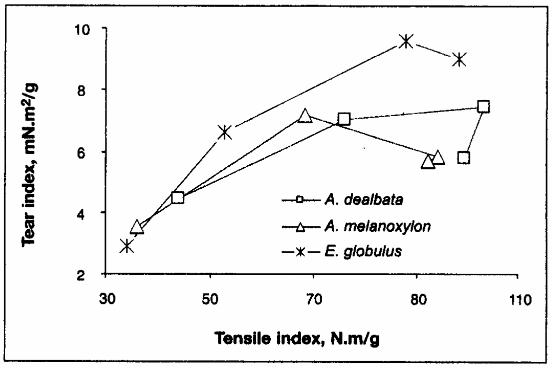

Fig. 9 Evolution of tear index as a function of tensile index, for Acacia and *E. globulus*.

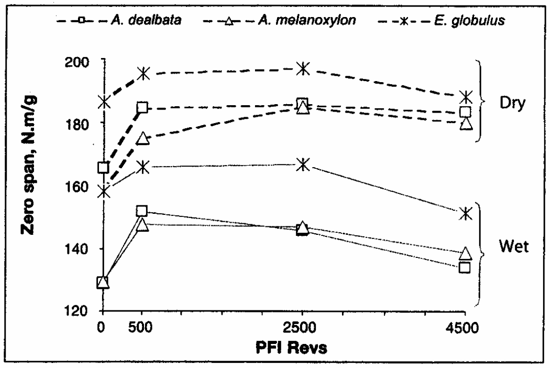

Fig. 10 Evolution of zero-span tensile strength with refining, for Acacia and *E. globulus*.

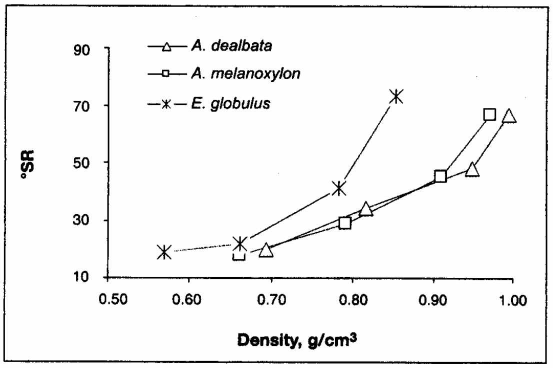

Fig. 11 Evolution of the Schopper Riegler degree (°SR) with density, for Acacia and *E. globulus*.

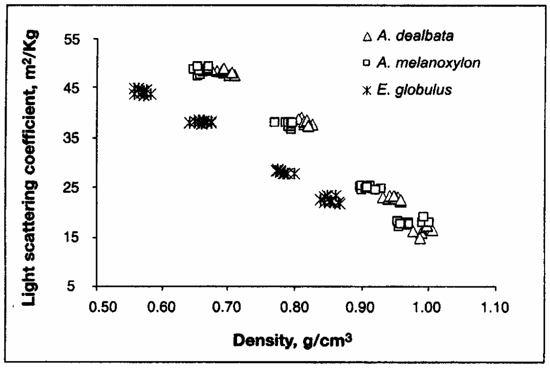

Fig. 12 Light scattering coefficient vs density, for Acacia and *E. globulus*.

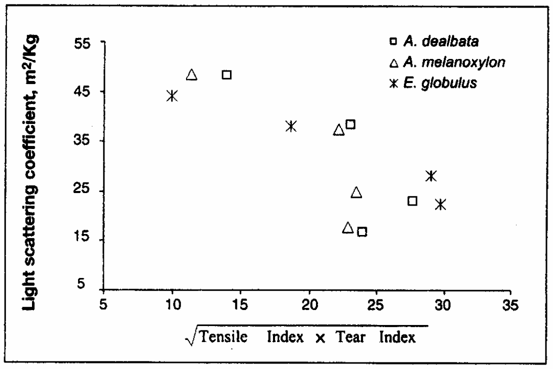

Fig. 13 Light scattering coefficient vs strength resistance, for Acacia and *E. globulus*.

The unbleached and bleached pulp viscosity is similar and no differences were detected in the bleaching process concerning bleachability. However, the lower digester production, due to the very low wood basic density, is a very important disadvantage.

Acacia species, with their relatively short, flexible and collapsible fibres, have potential to produce papers with good tradeoffs between light scattering/tensile strength and smoothness/tensile strength, at low energy consumption in refining. However, in applications where bulk and tear and tensile strength are required, the Acacia species we studied are less competitive. In addition, according to our experience with other samples of the same species, variability within species is high, which means that the relative position of *E. globulus* and Acacia depends strongly on the samples selected for comparison. However, due to their high specific surface, Acacia fibres show great potential, at least for use in combination with *E. globulus*, in writing and printing paper production.

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