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The strength of bagasse fibre-reinforced composites

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The increasing board densities resulting from increased final platten pressure applied during production (or maximum moulding pressure) provides the reason for observations of similar increases in the Young's modulus and the tensile strength, when two phenol formaldehyde bonded boards which are reinforced with 80% and 90% by volume of bagasse fibres are examined. Scanning electron microscopy was carried out on the fracture zones to differentiate between the effects of varying formaldehyde content. However, even with differences in the sizes of the cavities formed at fracture and in the board densities, the observed modulus versus density and strength versus density curves follow exponential trends. By using the exponential trends, a single best linear tensile strength versus Young's modulus relationship is deduced for these varying fibre to matrix combinations.

1. Introduction

The efforts to utilize all available natural resources including plants have led to the production of roofing composites from cellulosic fibres. Developments such as these will supplement the present usage of synthetic fibres, which will be affected negatively by the failing oil resources [1]. Low Young's modulus cellulosic fibres such as begasse (*Saccharum officinarum* L.) act as useful crack growth inhibitors (crack stoppers). Two materials are considered, which contain begasse fibres used not only as crack stoppers or as fillers but as reinforcement at volume fractions of $v = 80\%$ and 90% within a phenol formaldehyde matrix [2].

It is established that, in general, man-made cellulose-based boards have densities increasing with the final platten pressure applied during production (or maximum moulding pressure), according to the pattern described in Fig. 1 [3]. These materials have mechanical properties dependent on density: the study described here verifies this point for the two materials considered.

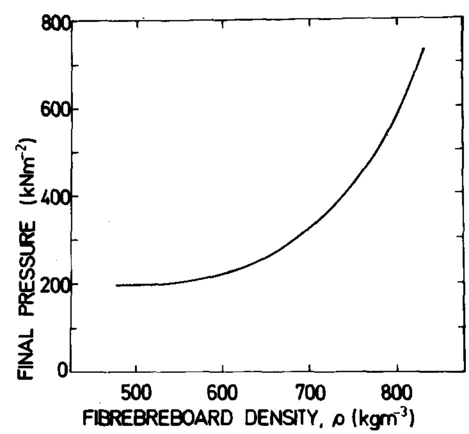

Figure 1 An illustration of the contribution of final pressure to the density of a cellulosic fibre-reinforced board.

Furthermore, by using evidence obtained in the UWI Laboratory by experimental analysis of mechanical properties and structure, it is now shown that there are patterns of Young's modulus (E) and tensile strength (σ_f) versus density (ρ) that are similar to the pressure versus density relationship. This study is extended to the fitting of the best exponential curves to these observed patterns, and finally to the development of a best single tensile strength versus Young's modulus relationship.

2. Description of samples

The two 2.5 mm thick materials analysed were designed specifically for roofing. The first material

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was produced locally according to a standard method ([2] p. 190) so that it contained randomly oriented begasse specimens (of length = 10 to 30 mm and cross-sectional area = 0.04 to 0.20 mm^2). The previously published properties of such man-made samples are $E = 4.89\ \mathrm{GN\,m^{-2}}$ and $\sigma_f = 28.4\ \mathrm{MN\,m^{-2}}$ ([2] p. 31). The samples contain by weight 61% (i.e. $v = 80\%$ by volume) of begasse specimens, 30% phenol formaldehyde (PF) resin, 0.05% penta, 5% ferric oxide pigment and 4% process oil.

The second material was produced by a second method ([2] p. 199) and submitted in a corrugated form by the Monsanto Research Corporation. Their published properties are $E = 1.72\ \mathrm{GN\,m^{-2}}$ and $\sigma_f = 7.78\ \mathrm{MN\,m^{-2}}$ at right angles to the direction of "10% orientation" ([2] p. 32). This "10% orientation" refers to the alignment of 10% begasse fibres in one direction while the other 90% of fibres were randomly oriented.* The locally determined figures for the constituents are by weight 78.7% (i.e. $v = 90\%$ by volume) small begasse specimens, 4.14% PF resin and 17.2% other matrix constituents.

3. Methods of analysis

The densities of samples cut and shaped rectangularly for Young's modulus determination were calculated from dimensions measured with a Vernier caliper, a micrometer, a meter rule, and a 2 kg balance. These specimens had lengths of about 300 mm and cross-sectional areas in the range 45 to 60 mm^2. In particular the corrugated samples were cut such that their lengths were parallel to the troughs and crests so that flat specimens were obtained without causing disturbance to the structure of the board. The present results, therefore, describe the properties at right angles to the axis of 10% orientation. The Young's moduli were determined by applying the three-point bend method to three samples at $v = 80\%$ and five samples at $v = 90\%$; in addition, each of the latter samples was inverted so that the top for the initial Young's modulus analysis was turned downwards for a second Young's modulus determination. All of the samples were subjected to tensile testing, but only after those with $v = 90\%$ were reduced to dumb-bell-shaped specimens having the narrow region in the range 10 to 20 mm^2. This reduction in area was necessary in order to prevent the specimens from failing as a result of pressure increases at the grips during extension.

The tensile strengths were measured using a Monsanto tensometer type TEK/2/9125. Portions of the fractured specimens were examined using an ISI-60 scanning electron microscope (SEM).

4. Results and discussion

The trends for Young's modulus (Fig. 2) and tensile strength (Fig. 3) against density resembles that for the final platten pressure applied against density, and these mechanical properties further appeared to increase exponentially with density.

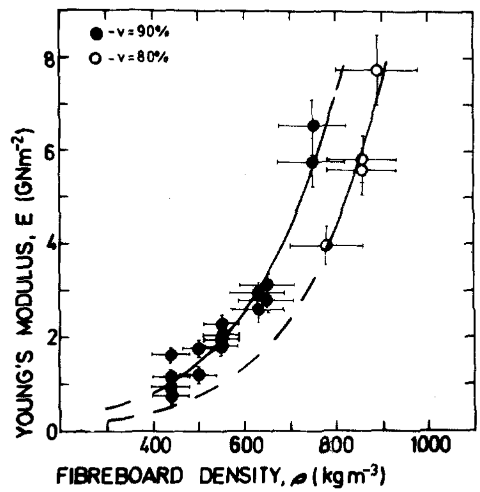

Figure 2 A plot of the observed Young's moduli against density for the bagasse boards designed for roofing, on which deduced curves are superimposed.

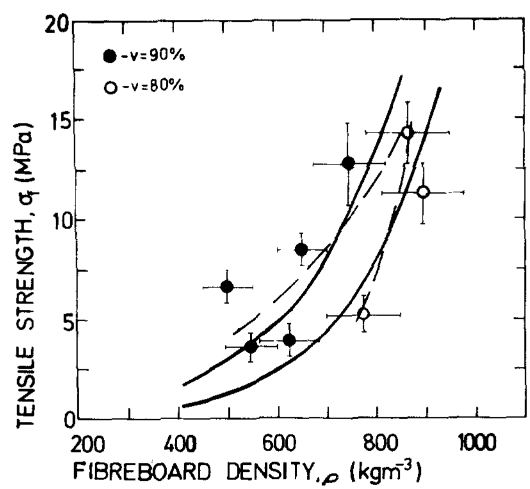

Figure 3 A plot of the observed tensile strength against density for the bagasse boards, on which deduced curves are superimposed.

*Information obtained by personal communication with G. L. Ball III.

Prior to obtaining the empirical fits, initial predictions of the properties were made using the following rule of mixtures equation:

$$X = \sum v_i X_i, \qquad (1)$$

where X is the material property, and X_i the corresponding property of the component (fibre, etc) at volume fraction v_i. Allowance was therefore made for differences in resin content and efficiency factors in the range $\frac{1}{6}$ to $\frac{1}{3}$ were applied to allow for random fibre orientation. However, even with allowance for the volume fraction of the empty regions, the predictions of strength were particularly inadequate since they were rather high.

All the samples described had very linear load versus depression curves for the three-point bend test, even though about 35% of the load had to be removed before an appreciable reduction occurred in the level of depression for the specimens with $v = 90\%$. This effect indicated that there was separation of the begasse fibres from the remainder of the board for these samples with low resin content. This argument is further supported by the SEM analysis which reveals that, as compared to the case where $v = 80\%$, larger cavities are obtained within the fracture zones of the samples with $v = 90\%$.

The mechanical properties determined in this study are comparable to those initially reported ([2] pp.31,32), but there are no previously stated mean density or estimated ranges of densities. In this particular study, the mean density is found to be $\bar{\rho} = 0.85 \times 10^3$ kg m^{-3} with a standard deviation of S.D. = 0.05×10^3 kg m^{-3} for $v = 80\%$, and $\bar{\rho} = 0.56 \times 10^3$ kg m^{-3} with S.D. = 0.10×10^3 kg m^{-3} for $v = 90\%$, showing that as is expected the densities are also increased for larger resin content and lower fibre content.

The patterns obtained from these samples, as illustrated for E in Fig. 2 and for σ_f by the discontinuous curves in Fig. 3, are the results of a series of regressions of the logarithm of E or σ_f plus a constant against ρ. The regressions were performed separately for E and σ_f with consideration given to each type of sample (having $v = 80\%$ and $v = 90\%$). For example a regression of $\log_e(E + k_1)$ against ρ, where k_1 was an initial guess, resulted in:

$$E + k_1 = \exp|k_2\rho + k_3|, \qquad (2)$$

where k_2 and k_3 were constants of regression. E and ρ will be zero at the same time if

$$k_1 = e^{k_3}. \qquad (3)$$

This condition is applied since it is only realistic to expect that a material with zero density will exhibit zero stiffness (which is obtained for zero Young's modulus) and vice-versa. The values of e^{k_3} and/or the mean of k_1 and e^{k_3} were used as new approximations of k_1. The regressions were repeated until k_1 and e^{k_3} were within 0.01% of each other so that Equation 3 is applicable.

This method was repeated for $v = 90\%$ and for both sets of samples with E replaced by σ_f.

The results are summarized in Table I along with the correlation coefficients of the predicted versus the measured results: these coefficients are acceptably high for the Young's modulus, E. The reliability is tested by an examination of the deduced tensile strength versus Young's modulus trends using the equations which are given in Table II. These trends are illustrated by the broken curves in Fig. 4. The plotted data for both materials have trends which differ negligibly. Therefore, the straight line passing through the origin and the intersection of the deduced curves appears to be a reasonable representation. This

TABLE I Regression curves for mechanical properties versus density

Fibre volume content	Regression curves	Correlation coefficients versus measured results
$v = 80\%$	$E = 0.047\,\|\exp(5.65 \times 10^{-3}\rho) - 1\|$ (GN m^{-2})	0.95 (at > 99.9% significance)
	$\sigma_f = 3.21\,\|\exp(9.70 \times 10^{-3}\rho)\|$ (MN m^{-2})	0.83 (at K 99.5% significance)
$v = 90\%$	$E = 0.127\,\|\exp(5.06 \times 10^{-3}\rho) - 1\|$ (GN m^{-2})	0.96 (at > 95.0% significance)
	$\sigma_f = 1.25\,\|\exp(2.95 \times 10^{-3}\rho) - 1\|$ (MN m^{-2})	0.82 (at ≈ 57.0% significance)

N.B. E trends were more reliably predicted.

TABLE II Best tensile strength–Young's modulus relationships

Method of determination	Equation	Correlation coefficient of predicted versus measured results
Trend deduced from previous regression curves (i.e. Fig. 4)	$\sigma_f = 1.89 \times 10^{-3} E$ $(\mathrm{N\,m^{-2}})$	0.85 (with > 99.9% significance)
Linear $\sigma_f - E$ regression	$\sigma_f = 1.46 \times 10^{-3} E + 2.42 \times 10^{6}$ $(\mathrm{N\,m^{-2}})$	0.79 (with > 99.9% significance)
Centroid approximation (i.e. line through origin with slope $= \Sigma\sigma_f/\Sigma E$	$\sigma_f = 2.12 \times 10^{-3} E$ $(\mathrm{N\,m^{-2}})$	0.80 (with > 99.9% significance)

general line is stated as follows:

$$\sigma_f = 1.89 \times 10^{-3} E. \tag{4}$$

In fact, this equation proved to be the best straight line representation of the observed results for the two following reasons:

(1) it was used to predict more acceptable values of strength than the other linear tensile strength versus Young's modulus curves which were examined in this study (Table II);

(2) it was more realistic than the linear tensile strength versus Young's modulus regression curve in predicting a zero value for the Young's modulus and the tensile strength simultaneously.

This best strength versus stiffness fit is used with the Young's modulus versus density relationships to derive the final strength versus density representation. The results are given as follows. For $v = 80\%$,

$$\sigma_f = 0.89\,|\exp(5.65 \times 10^{-3}\rho) - 1|\ (\mathrm{MN\,m^{-2}}), \tag{5}$$

and for $v = 90\%$,

$$\sigma_f = 0.24\,|\exp(5.06 \times 10^{-3}\rho) - 1|\ (\mathrm{MN\,m^{-2}}), \tag{6}$$

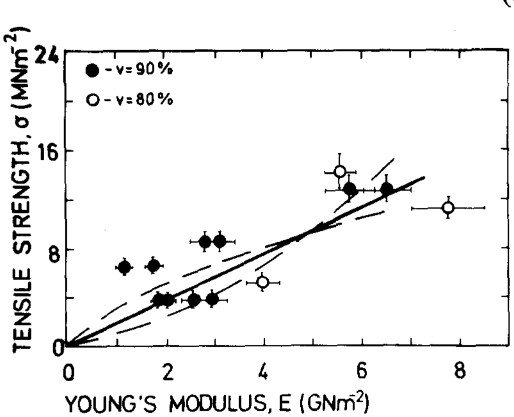

Figure 4 A plot of the tensile strengths against the Young's modulus for the bagasse boards, on which the deduced curves and the best straight line are superimposed.

which are represented by the continuous curves in Fig. 3. Equations 4 to 6 therefore, describe the interrelations of the properties (ρ, E and σ_f) for these bagasse fibre-reinforced structures with linear load–strain relationships to failure at mean strains of 0.3% for $v = 80\%$ and 0.2% for $v = 90\%$.

The transfer of stress within these type of materials is very important to the tensile strength and Young's modulus of the boards. Therefore, a production process aimed at obtaining maximum continuity between the fibres and the binder is essential. One major contributing factor is the influence of pressure on the flow of the binder between the fibres during production. The apparent separation which results from the applied strains and the cavities which result at fracture provide evidence of the types of weaknesses which characterize these low density boards. The fact that a large binder content increases the density and at the same time contributes to improving the continuity and the homogeneity within the matrix explains the reduction of the cavity sizes for $v = 80\%$ compared to $v = 90\%$. However, it is the application of increasing pressure which has control over the binder during production, and will therefore cause a significant improvement in the continuity as it increases the board density (Fig. 1). Furthermore, the small bagasse specimens are not simply used as fillers or as crack stoppers but as reinforcement. The latter function is emphasized by the fact that strengths greater than $30\,\mathrm{MN\,m^{-2}}$ were obtained for the low resin content samples along the direction of 10% orientation ([2] p. 32). It follows that as opposed to the improvement obtained in the mechanical properties by increasing the applied pressure, the increasing resin content which means a decreasing fibre content, may produce a decrease in the mechanical properties.

The similarity of the results described in Figs. 2

and 3 to those in Fig. 1 shows that for increasing density, the Young's moduli and the tensile strengths increase in the same manner as the final pressure applied during production. As a result, the deduced tensile strength versus Young's modulus linear relationship (Fig. 4, Equation 4), which is common to boards of varying fibre to binder ratios, provides a most useful description of these materials.

5. Conclusions

Non-linear relationships of the Young's modulus and the tensile strengths with the density are obtained for bagasse fibre-reinforced–phenol formaldehyde resin bonded materials, from which a general relationship is deduced. This relationship is shown to be the best general description and is stated in Equation 4 as a linear dependence of the tensile strength on the Young's modulus.

References

1. A. R. FLOWER, *Sci. Amer.* **238-3** (1978) 42.
2. I. O. SALYER, G. L. BALL III, A. M. USMANI and D. W. WERKMEISTER, Development of Low Cost Roofing from Indigenous Materials of Developing Nations, AID/US (1975) pp. 31, 32, 190, 199.
3. A. A. MOSLEMI, "Particleboard", Vol. 2 (Southern Illinois University Press, Carbondale and Edwardsville, 1974) p. 114.

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