

Particleboards from Peanut-Shell Flour

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Received 30 June 2004; accepted 28 December 2004

DOI 10.1002/app.21847

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Peanuts have been cultivated worldwide for hundreds, if not thousands, of years. However, most peanuts are sold without the shell, and so large quantities of peanut shells remain as byproducts in the field, not being used properly. In this work, the feasibility of making particleboard from milled peanut shells was studied. To obtain medium-density panels, a low compaction pressure and a high fiber content were used. The physical and mechanical properties of the panels were similar to those reported for wood-based particleboard when 80 wt % filler was used. The void content of the panels was experimentally deter-

mined and used in an attempt to predict the mechanical response of the panels. The stiffness of the particleboard could be greatly improved by a reduction of the porosity, but even a low void content had a critical effect on the strength of the composites. The stiffness of the composites could only be reasonably represented with simple theoretical models when the effect of the porosity was incorporated. © 2005 Wiley Periodicals, Inc. *J Appl Polym Sci* 97: 916–923, 2005

Key words: composites; fillers; mechanical properties; thermosets

INTRODUCTION

Particleboard is a panel material manufactured under pressure, essentially from particles of wood, other lignocellulosic fibrous materials, or both combined with synthetic resins and bonded together under heat and pressure in a hot press.¹ The past 40 years have seen successful developments within the forest product industry, especially in products generally called particleboards. Much of this success can be attributed to the decided economic advantage of low-cost wood raw materials and inexpensive processing with binders.¹ The construction and furniture industries are the largest markets for the board. Particleboards have found applications in floor, wall, and ceiling panels, office dividers, bulletin boards, furniture, cabinets, countertops, and desk tops.^{2,3}

The potential for using lignocellulosics from agricultural residues and annual fiber crops in place of wood as raw materials or panel products has received considerable attention in recent years. Ntalos and Grigoriou⁴ studied the effectiveness of vine prunings, a lignocellulosic agricultural residue from vines, as a replacement for wood as the raw material for particleboard production. Papadopoulos and Hague⁵ investi-

gated the technical feasibility of making single-layer experimental particleboards from mixtures of flax shiv (the woody core generated as a waste byproduct from the flax-fiber/linen industry) and wood chips. Nemli et al.⁶ analyzed the suitability of kiwi prunings for particleboard manufacturing, and Gerardi et al.⁷ studied the feasibility of using steam-treated rice-industry residues as an alternative feedstock for the wood-based particleboard industry in Italy. Moreover, Mo et al.⁸ studied the physical properties of medium-density wheat-straw particleboard with different adhesives.

Particleboard with a density range of 0.59–0.8 g/cm³ is designated as medium-density (ASTM D 1554-86). It has broad applications for both structural and nonstructural uses. Several types of adhesives have been applied in producing particleboard. The most commonly used resins are urea formaldehyde, phenol formaldehyde (PF), and methylene diphenyl diisocyanate.^{8,9}

PF resins provide high strength and are extremely resistant to moisture; this prevents delamination and gives excellent temperature stability, in part because of the flexible nature of these resins.^{1,10} In addition, they exhibit excellent thermal and chemical resistance with low flammability, smoke density, and toxicity^{10,11} and can generate chemical bonding with the lignocellulosic reinforcements, leading to strong forces between the fiber and resin.^{12,13} Thus, a high compatibility in the vegetable-fiber/polymer system is achieved.

During the processing of phenolic resins, the byproduct of the polycondensation reaction is mostly water. Hence, the evaporation of this byproduct dur-

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Contract grant sponsor: National Research Council of República Argentina; contract grant number: PEI 1146.

Contract grant sponsor: Antorchas Foundation (Argentina); contract grant number: 14116/177.

ing the curing of the polymer can lead to voids in the final material. The most liquid and castable resol contains methylene and ether bonds, which have reactive methyl end groups and thus can be cured via acid or the application of heat. In practical applications, the most frequent method for conversion is heat-activated curing. At higher temperatures, the ether bonds between the resol links shift to methylene bonds by producing formaldehyde. This formaldehyde can react once again with the phenol (or eventually with the OH groups present in the natural reinforcement). The relatively short branched connections via methylene bonds in phenolic resins result in brittle mechanical properties that can be slightly improved by the addition of fillers.¹¹

Peanuts have been cultivated worldwide for hundreds, if not thousands, of years. However, most peanuts are sold without the shell, and so large quantities of peanut shells remain as byproducts in the field, not being used properly.

The aim of this work is to study the feasibility of making experimental particleboards from milled peanut shells. To obtain medium-density panels, a low compaction pressure and high fiber content were used. The particleboards were physically and mechanically characterized. The void content of the panels was experimentally determined and used in an attempt to predict the mechanical response of the panels.

REINFORCEMENT THEORIES FOR PARTICULATE POLYMER COMPOSITES

In conventional unidirectional and continuous composites, the traditional way of predicting composite stiffness is to apply the simple rule of mixtures.¹⁴ For a random distribution of the individual phases (particulate composite), the model is also useful, simplifying the arrangement to a two-phase model in which average stresses and strains are considered to exist in each of the phases.¹⁵ The upper and lower bounds for this model are given by eqs. (1) and (2), respectively:

$$E_c = V_f E_f + (1 - V_f) E_m \quad (1)$$

$$E_c = \frac{E_f E_m}{(1 - V_f) E_f + V_f E_m} \quad (2)$$

where E is the elastic modulus and V is the volumetric fraction. The subscripts c , f , and m indicate the composite, fiber, and matrix, respectively.

Improved bounds for the modulus of two-phase media were obtained by Paul and by Ishai and Cohen.¹⁵ In the approximate solution obtained by Paul, the constituents are assumed to be in a state of macroscopically homogeneous stress. Perfect adhesion at the interface of a cubic inclusion embedded in a cubic

matrix is proposed. Under this assumption, when a uniform stress is applied at the boundary, the elastic modulus of the composite is given by

$$E_c = E_m \left[\frac{1 + (E_f/E_m - 1)V_f^{2/3}}{1 + (E_f/E_m - 1)(V_f^{2/3} - V_f)} \right] \quad (3)$$

Applying the same model, but assuming a uniform displacement at the boundary, Ishai and Cohen obtained the following equation:

$$E_c = E_m \left[1 + \frac{V_f}{(E_f/E_m)/(E_f/E_m - 1) - V_f^{1/3}} \right] \quad (4)$$

Another interesting approach is the simple model proposed by Counto,¹⁴ which assumes perfect bonding between the particles and the matrix. In this case, the modulus of the composite is given by

$$\frac{1}{E_c} = \frac{1 - V_f^{1/2}}{E_m} + \frac{1}{(1 - V_f^{1/2})/V_f^{1/2} E_m + E_f} \quad (5)$$

Even though these models have proved to be a good approximation to composite properties, all of them assume that the composite porosity content is equal to zero.¹⁴ Besides the effect of lowering the composite load-bearing volume, the porosity also affects the composite mechanical properties by introducing stress concentrations into the material.¹⁴ Therefore, as these effect were not included in the derivation of eqs. (1)–(5), they will not be able to represent the stiffness of a particleboard.

One alternative to including the effect of porosity in calculating the stiffness of a composite material consists of attributing all the voids to the matrix phase through the calculation of an effective matrix Young's modulus and then using it instead of the true matrix modulus in conventional models. This approach was successfully applied previously.¹⁶

Alternatively, Madsen and Lilholt¹⁴ proposed that the effect of porosity on material stiffness can be approximated by

$$E_v = E_d(1 - V_v)^2 \quad (6)$$

where the subscripts d and v denote the fully dense material and the porous material, respectively.

On the other hand, the effect of porosity on the mechanical properties has been extensively studied for ceramic materials. Ceramics have inherently random microstructures, and the pores in these materials have random shapes, sizes, and distributions;¹⁷ this is the same behavior expected in particleboards. A relation of the form

$$E_v = E_d(1 - V_v)^n \quad (7)$$

TABLE I
Physical and Mechanical Properties of Resol

Density (g/cm ³)	1.2433 ± 0.04
Strength (MPa)	94 ± 10.5
Elongation at break (%)	0.03 ± 0.007
E (GPa)	2.58 ± 0.46

where the constant n is the stress concentration factor due to the presence of pores in the material and is dependent on the pore geometry, has been successfully applied to describe all the data over the entire range of porosity.¹⁸

The models for predicting the strength of filled systems are less developed than the models for predicting the moduli. However, the Nielsen equation,¹⁵ which was derived for the case of perfect adhesion between the phases, assuming rigorous Hookean behavior up to breaking strains, seems to be useful in this work because the tensile behavior of our particleboards fulfills the assumptions (where σ = strength):

$$\sigma_c = \sigma_m \frac{E_c}{E_m} (1 - V_f^{1/3}) \quad (8)$$

Finally, Danusso and Tieghi¹⁹ suggested for cases of interfacial adhesion between the phases, on a purely empirical basis, the following estimation with three fitting parameters (a , b , and c):

$$\sigma_c = \sigma_m \left(\frac{1 - V_f}{a + bV_f + cV_f^2} \right) \quad (9)$$

EXPERIMENTAL

Materials

A commercial alcoholic solution, liquid resol (R472, Atanor, Buenos Aires, Argentina), with 60.6 wt % solids, a viscosity of 230 cp at 19°C, a pH of 8.0–8.6 at 25°C, and a water concentration of 12–20 wt %, was used as the matrix. The resol was produced by the condensation reaction of phenol with formaldehyde in a basic medium. The first step of the reaction was the formation of addition compounds known as methylol derivatives (the reaction taking place at the ortho or para position). In the presence of alkaline catalysts and with more formaldehyde, the methylol phenols condensed either through methylene linkages or through ether linkages. In the latter case, the subsequent loss of formaldehyde could occur with methylene bridge formation. This type of product was soluble and fusible but contained alcohol groups. When the reactions leading to their formation were carried out further, large numbers of phenolic nuclei could condense to form networks.

The mechanical and physical properties of the pure resol, shown in Table I, were obtained from the liter-

ature.²⁰ The mechanical properties were determined with flexural tests (ASTM D 790) because of the inherent brittleness of the matrix, and the density was determined by pycnometry.

Peanut shells (Manisur S.A., Provincia de Córdoba, Argentina) were milled with an IKA Labortechnik 250-mL mill (Staufen, Germany), and the obtained powder was sieved. Particles greater than 370 μm were rejected. Before being used, peanut shells were dried at 70°C in a vacuum oven until a constant weight was achieved. Figure 1 shows the particle size distribution used in this work, presented as a percentage of the weight (dry base) versus the average diameter.

Particleboard preparation

To obtain medium-density particleboards, the resol was added drop by drop to the peanut-shell powder, and manual premixing was performed. After the paste was homogenized, it was added to the IKA Labortechnik 250-mL mill, and a 3-min mixing step was realized. The paste was finally dried at 37°C during 3–6 h (depending on the concentration of resol) to obtain a dried powder through the evaporation of the ethylic alcohol that came with the commercial resol. After that, the mixture was placed in an aluminum mold (145 mm and ca. 3 mm thick), and a pressure of 6 kg/cm² was applied to preform the paste. The curing process was carried out without pressure, with the following thermal schedule: 30 min at 90°C, 60 min at 140°C, and 10 min at 160°C.

High-density particleboards were prepared for comparison. In this case, resol and peanut shells were mixed in a Brabender-type mixer (volume capacity = 250 cm³) for about 15 min. The paste was filled in the metal mold, and the reaction was carried out un-

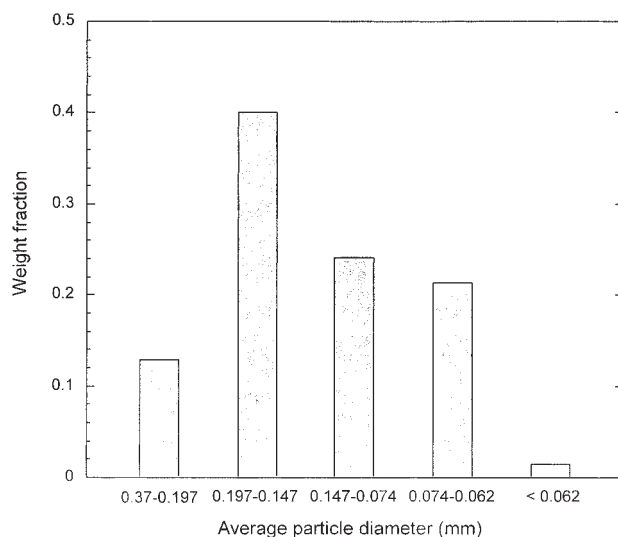


Figure 1 Particle size distribution of peanut-shell flour.

der pressure (2.2 kg/cm²) according to the following schedule: 1 h at 90°C, 1.5 h at 140°C, and finally 0.5 h at 175°C. The pressure was also maintained during the cooling step (20 min to room temperature).

Methods

The theoretical value for the volume fraction of the filler, V_{ft} , was calculated as follows:

$$V_{ft} = (W_f/\rho_f)[(W_f/\rho_f) + (W_m/\rho_m)] \quad (10)$$

where W_i is the weight fraction, ρ_i is the density, and subscripts f and m denote the fiber and matrix, respectively.

The theoretical density of the composites, ρ_t , was calculated from the individual phases densities, based on the mass fraction of each:

$$\frac{1}{\rho_t} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \quad (11)$$

The density of the composites, ρ_c , was measured by pycnometry in distilled and degassed water at 20°C. Then, the void volume fraction, V_v , was calculated as follows:

$$V_v = 1 - \frac{\rho_c}{\rho_t} \quad (12)$$

Finally, the actual volume fraction of filler was calculated as follows:

$$V_f = V_{ft}/(1 + V_v) \quad (13)$$

Tensile and three-point-bending tests were performed with an Instron 8501 (Buckinghamshire, England) universal testing machine according to ASTM D 638 and ASTM D 790M (procedure A), respectively. Specimen type IV was used for the tensile tests. At least five specimens for each condition were tested.

The thickness swelling and water absorption were determined according to ASTM D 570 after 24 h of immersion in distilled water.

Thermogravimetric tests were performed with a Seiko Instruments SII Exstar 6000 thermogravimetric analyzer (Chiba, Japan). The measurements were carried out in an air atmosphere from room temperature to 450°C at a heating rate of 10°C/min. The sample weight was about 10 mg.

The fractured surfaces of the tensile-tested composites were observed by scanning electron microscopy (SEM) with a Philips JEOL 35 CF microscope (Akishima, Japan). The surfaces were previously coated with gold to avoid charging under the electron beam.

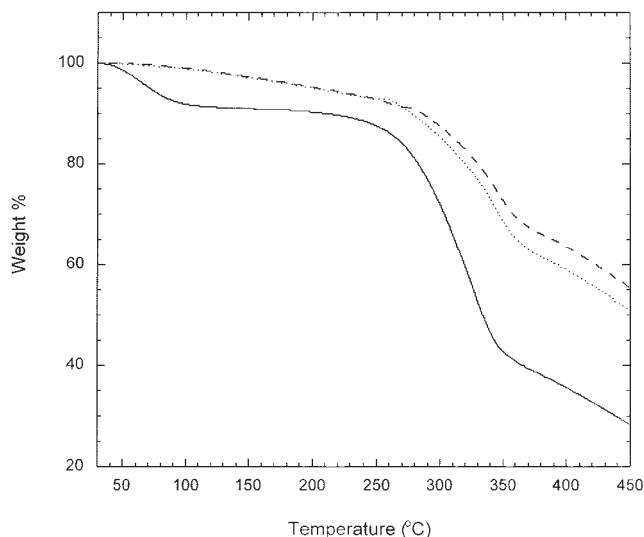


Figure 2 Thermogravimetric curves of the filler and particleboard. The peanut-shell-flour concentration was (—) 100, (· · ·) 60, and (---) 50 wt %.

RESULTS AND DISCUSSION

Phenolic resins are excellent flame-retardant and heat-resistant thermosets, in comparison with other polymeric materials. They are more difficult to burn, release less smoke and toxic gas, and generate the highest amount of carbon residues.^{21,22} The thermal decomposition of phenolic resins has three stages.¹² Before 300°C, there is a small weight loss mainly due to excess phenol, aldehyde, oligomer, and water, which are released. The thermal decomposition within the range of 300–600°C presents products such as CO, CO₂, benzaldehyde, phenol, and its polymers, with random chain scission and the initial formation of char. It is thought to be the temperature range in which major decomposition takes place. For temperatures above 600°C, dehydration occurs, and a carbon-like structure, char, is gradually formed, with carbon monoxide as a byproduct. Beyond this temperature, the curve is flat.²²

Figure 2 shows the thermogravimetric curves for peanut-shell flour and composites made with 50 and 60 wt % reinforcement. In general, a loss of water can be observed below 120°C, and further thermal degradation appears to take place as a two-step process because the tests were not continued beyond 450°C.

From the thermograms, several parameters were evaluated: (1) the amount of desorbed water (as the percentage of mass lost below 120°C), (2) the onset of thermal degradation (T_d), (3) the temperature at which half of the initial mass of the sample was lost (T_b), and (4) the residual char at 450°C (as a percentage). Because the samples presented different amounts of absorbed water and the rate of weight loss was different from sample to sample, T_d was taken as the temperature at which the sample lost 5% of its initial weight,

TABLE II
Thermal Degradation Data of Peanut-Shell Flour and Composites at 10°C/min in Air

Peanut shell (%)	Desorbed water (%)	T_d (°C)	T_b (°C)	Char (%)
50	1.56	238.90	474.30	56.3
60	1.728	239.70	458.60	51.6
100	8.725	256.80	342.00	31.1

based in the weight of the dry sample, that is, after water desorption. The same basis was adopted for items 3 and 4. From these results, summarized in Table II, it can be seen that the onset of degradation occurs at lower temperatures as the concentration of peanut shells increases, but the opposite behavior was noticed for T_b . This indicates that degradation of the matrix begins at lower temperatures, but with a lower rate of decomposition than that of the neat peanut shell. Moreover, the percentage of residual char left at 450°C decreases with the filler content because the amount of resin decreases. Vegetable fillers, including peanut shells, are formed mainly of cellulose, hemicellulose, and lignin. The cellulose almost decomposes fully into volatile products,²² leaving behind only a very small percentage of char, and thus only the hemicellulose and lignin (minor components) contribute to the char production.

Moreover, the amount of water absorbed by the peanut-shell flour is highly reduced when it is compounded to form a particleboard because of the restricted diffusion of water into the thermoset.

Isothermal thermogravimetric tests (not shown) were also performed for 2 h on peanut-shell flour at 180 and 190°C, temperatures higher than those used in the curing process of the composites. In both cases, the mass lost during the whole run was less than 9%, and this indicates that only the moisture adsorbed by the flour was eliminated. This behavior ensures that no thermal degradation will occur in the filler during composite preparation.

Table III shows the experimentally determined particleboard density. The density of the composites decreases as the peanut-shell concentration increases. If all the capillaries of the peanut shell were filled with resin, the density of the filler in the composite would approach the density of the cell wall (1.53 g/cm³, ref.

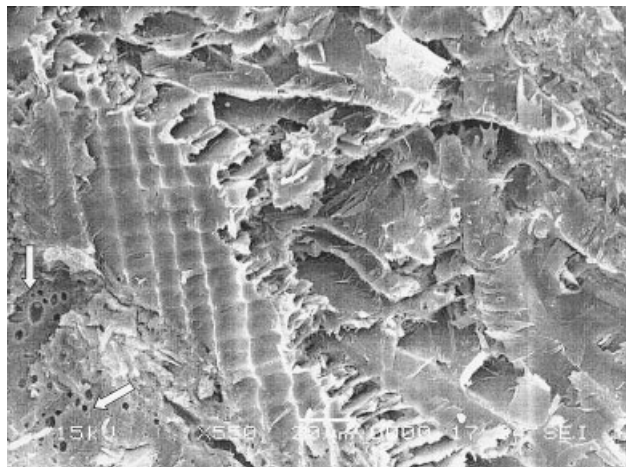


Figure 3 SEM micrograph of 50 wt % particleboard.

23). In this case, the density of the reinforcement being higher than that of the matrix, an increase in the density of the samples with the filler content would be expected if there were no voids.²⁴ Thus, the void content of each sample was calculated with eq. (12) and is reported in Table III. As expected, the porosity of the particleboards increases with the filler content. On the other hand, it is possible to obtain medium-density particleboards from peanut shells, and a density similar to that of particleboards made from wood (650 kg/m³, ref. 7) was obtained when 80 wt % filler was used.

An SEM micrograph of the fracture surface of the composite made from 50 wt % is shown in Figure 3. It is difficult to differentiate the filler from the matrix because there are no gaps (separations) between them. This confirms the high compatibility between both phases. The matrix zone is revealed by the brittle fracture, as indicated by the arrows, and by the presence of voids, which were produced by the evaporation of water during curing. As mentioned previously, the addition of filler leads to more ductile behavior during fracture, which can be observed in the upper right part of the photograph.

The weight gain and thickness swelling due to water absorption are also reported in Table III. Both increase with the filler content because the porosity content also increases. As the porosity increases, the water finds less resistance to penetration into the sam-

TABLE III
Physical Properties of Peanut-Shell Composites

Fiber content (wt %)	Density (kg/m ³)	Void content (vol %)	Water absorption (wt %)	Thickness swelling (%)
50	1040 ± 20	19.5	27.36 ± 1.59	2.70 ± 0.22
60	1030 ± 20	20.9	30.74 ± 2.81	2.74 ± 0.091
70	840 ± 22	29.2	54.30 ± 2.25	4.54 ± 0.42
80	690 ± 31	34.6	76.72 ± 12.08	5.27 ± 0.42

TABLE IV
Mechanical Properties of Peanut-Shell Medium-Density Particleboards

Fiber content (wt %)	Tensile modulus (GPa)	Tensile maximum stress (MPa)	Flexural modulus (GPa)	Flexural maximum stress (MPa)
50	1.485 ± 0.12	11.40 ± 3.00	2.600 ± 0.290	14.06 ± 2.56
60	1.209 ± 0.11	8.00 ± 1.04	2.215 ± 0.208	12.98 ± 1.873
70	0.546 ± 0.035	3.00 ± 0.38	1.226 ± 0.087	7.00 ± 0.35
80	0.206 ± 0.042	0.96 ± 0.14	0.425 ± 0.065	1.70 ± 0.158

ple, or in other words, water diffusion is more difficult as the density of the particleboard increases.⁶ The measured values are comparable to those of other particleboards made from vegetable reinforcements.⁵ On the other hand, the thickness swelling is very low, compared with moisture sorption, because it is more affected by the bond quality²⁵ and adhesive properties, and as discussed previously, the compatibility between the filler and the matrix is excellent in this case.

Table IV shows the mechanical properties of particleboards determined in tensile and flexural tests. Both the moduli and strengths decrease as the filler content increases because the void content also increases. The porosity reduces the load-bearing volume of the sample and introduces stress concentrations, which make the material less stiff and resistant. However, even the tensile strength of the 80 wt % particleboard is in the range of those found in wood particleboards (≥ 0.35 MPa, ref. 7).

Selected properties of high-density composites from resol and peanut-shell flour prepared for comparison are reported in Table V. First, it was not possible to obtain a composite with no voids because the evaporation of water and solvents from the resol during curing led to porous systems, although pressure was applied. Both the modulus and strength increase with the filler content because the porosity of these composites is relatively low, and thus the reduction of the load-bearing volume is not as important as it is for medium-density particleboards. Moreover, the tensile strength of the high-density composites is in the same range as that of the medium-density one, and this indicates that even a low void concentration has a critical effect on the strength of the composites because of the stress concentrations introduced by porosity. On the other hand, high-density particleboards

exhibit much higher moduli than the corresponding medium-density ones, and this indicates that the stiffness of the composites could be greatly improved by the reduction of the void content.

Modeling the particleboard mechanical behavior

Because of a lack of information about peanut-shell stiffness, the range of 4.9–14 GPa, suggested by Buttre²⁶ for the modulus of saw dust, was adopted. Therefore, in the following calculations, a value of 10 GPa was taken as Young's modulus of the peanut-shell flour. However, the effect of the filler modulus on the composite predictions will be discussed later.

Equations (1)–(5) were used to model the experimental modulus as a function of the filler volume fraction. First, all the selected theoretical models predict a continuous increase in the composite modulus with the filler concentration if Young's modulus of the fiber is higher than that of the matrix, yet the opposite behavior was experimentally observed. Thus, to reverse this tendency, two different approaches were used.

Figure 4 shows the experimental tensile and flexural moduli together with the fitting curves obtained with the effective matrix modulus as a function of the actual fiber volume fraction. In all cases, eqs. (1)–(5) were applied two times: first to calculate an effective matrix modulus with the void volume fraction as the filler concentration with the modulus equal to zero and second to calculate the composite modulus with the effective matrix modulus as the modulus of the matrix. An exception was made with eq. (2), for which the effective matrix modulus was calculated with the upper bond of the rule of mixtures [eq. (1)]. The use of a matrix modulus corrected by porosity is not suffi-

TABLE V
Physical and Mechanical Properties of Peanut-Shell High-Density Particleboards

Fiber content (wt %)	Tensile modulus (GPa)	Tensile maximum stress (MPa)	Density (kg/m ³)		Void content (vol %)
			Experimental	Theoretical	
40	1.36 ± 0.13	11.20 ± 6.9	—	—	—
50	1.96 ± 0.26	8.04 ± 3.6	1279 ± 14.9	1372	6.8
60	3.15 ± 0.65	15.37 ± 7.82	1296 ± 9.65	1401	7.5

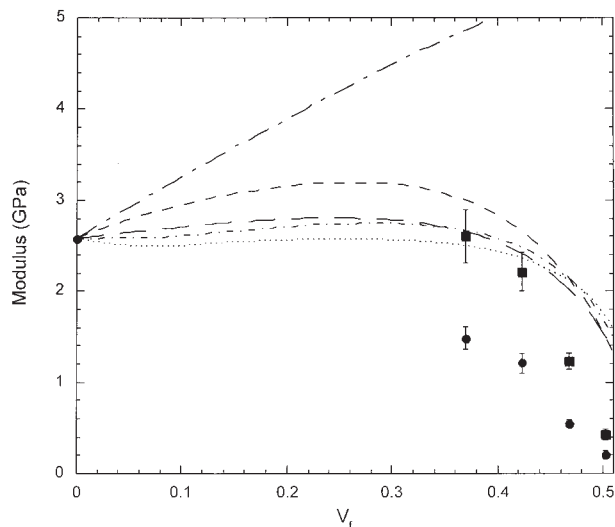


Figure 4 Experimental (●) tensile and (■) flexural moduli and fitting curves (lines) obtained with the effective matrix modulus approach as a function of the actual fiber volume fraction (V_f): (—) upper bound, (---) lower bound, (- · -) Ishai-Cohen, (·· ·) Paul, and (-) Counto models.

cient to obtain good agreement, especially at high filler (high void) contents.

In the second method, the correction derived by MacKenzie²⁷ and successfully applied by Madsen and Lilholt¹⁴ in a recent publication was used. Figure 5 shows the predictions of eqs. (1)–(5), corrected by eq. (6), as well as the experimental values as a function of the actual fiber volume fraction. The fittings get closer to the experimental data, although none of the models

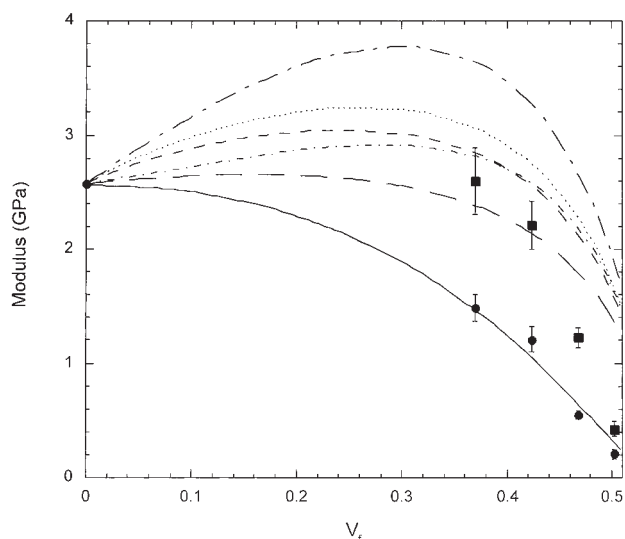


Figure 5 Experimental (●) tensile and (■) flexural moduli and fitting curves (lines) obtained with the void correction approach as a function of the actual fiber volume fraction (V_f). The following models were corrected with eq. (6): (—) upper bound, (---) lower bound, (- · -) Ishai-Cohen, (·· ·) Paul, and (-) Counto. (—) The lower-bound model was corrected with eq. (7).

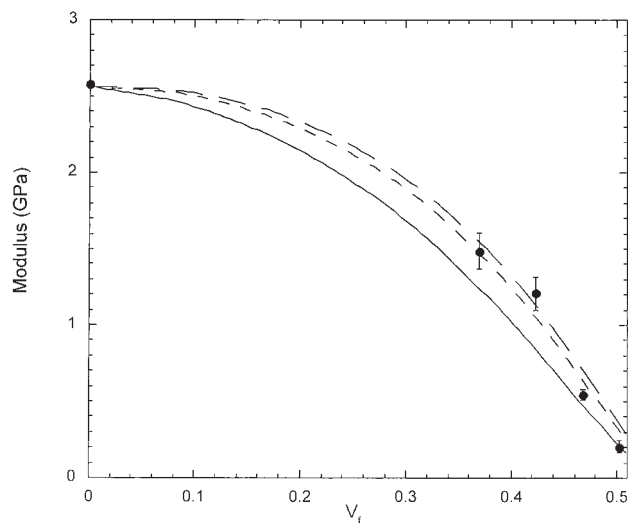


Figure 6 Fitting curves with the lower bound corrected by eq. (7) as a function of E_f : (---) 14, (---) 10, and (—) 4.9 GPa and (●) experimental tensile modulus.

successfully represent them. The lower bound of the rule of mixtures is, as expected, the model that gives the lowest values and thus the best fit.

The inability of both approaches to accurately model the experimental data, especially at higher filler contents, can be attributed to different facts that were not considered in the development of the equations. In practice, the particle distribution may be less homogeneous as the particles may not be completely separated from one another (e.g., aggregates of smaller particles may be present). Thus, the applied stress will then not be distributed evenly between the particles and the aggregates, and the assumption of either isostress or isostrain will not be valid.²⁸ In addition, the amount of the binder would be not enough to bound the filler particles together, and hence only part of the filler would act as a reinforcement.

The correction proposed in eq. (7), which was proved to be useful for calculating the modulus of porous ceramic materials, was also used. The solid line in Figure 5 represents the fitting calculated with the lower bond of the rule of mixture corrected by eq. (7). The constant n must be equal to 4 to obtain the best agreement with the experimental data. This value was in the range of those found for porous ceramics¹⁷ and represents the stress concentration factor due to the presence of pores in the material. A factor higher than 2 is necessary to obtain a reasonable agreement with experimental results.

Finally, Figure 6 shows the predictions obtained with eq. (2) corrected by eq. (7) when different values are used as the peanut-shell Young's modulus. Although the upper limit (14 GPa) represents properly the data at lower filler volume fractions, the lower limit (4.9 GPa) prediction is closer to the experimental points for higher filler concentrations. However, the

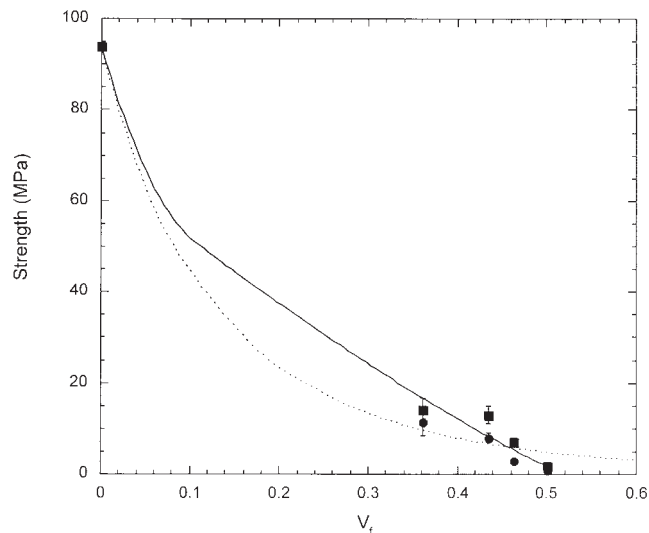


Figure 7 Experimental (●) tensile and (■) flexural strengths and fitting curves (lines) obtained with eqs. (—) (8) and (- - -) (9).

adopted value of 10 GPa seems to be a good average to model the composite modulus in the whole range of concentrations.

Figure 7 shows the predictions of eqs. (8) and (9) together with experimental tensile and flexural strength data. Both equations, derived with consideration of adhesion between the filler and matrix, give reasonable fittings. In the Nielsen equation, the experimental values for the composite tensile modulus are used, so the influence of porosity on the strength is indirectly considered. Besides, no fitting empirical parameters were needed to obtain good agreement with the experimental data. On the other hand, eq. (9) is able to correlate all data sets, simply varying the values of the fitting parameters.

CONCLUSIONS

It was possible to obtain medium-density particleboards from peanut-shell flour with pressure only for preforming the material. The physical and mechanical properties were similar to those reported for traditional particleboards (wood based) when 80 wt % filler was used. However, to achieve a low density, it was necessary to introduce a high void concentration in the composite material.

The stiffness of the particleboards could be greatly improved by the reduction of the porosity, but even a low void content had a critical effect on the strength of

the composites. On the other hand, the stiffness of the panels could only be reasonably represented with simple theoretical models when the effect of the porosity was incorporated.

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