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Mechanics of Polyropylene-Seed-Coat-Fibres Composites AndPolyropylene –Wood Fibres Composites-A Comparative Study

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Abstract

Forestry by-products have potential applications as components of wood composites. Replacement of conventional pine radiata wood-fibres by the fibres from the seeds (SCF) of the by-products, require determining and optimizing the mechanical properties to producing highest quality products. Response to mechanical stress is an important aspect to consider towards partial or full replacement of the wood-fibres by SCFs. In the present study the critical strain energy release rate, and the fracture toughness are derived from the published data. The present work uses rules of mixture to derive the mechanical and the physical properties of the SCF and relates the performance of the composites of the wood-fibres and the SCF to chemical composition, dispersion, weight and Vf of the fibres. We have also derived the Gc, the critical strain energy release rate, KIC, the fracture toughness of the composites.

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*Keywords:*wood-fibres; A. Polymer- matrix composites (PMCs); B. Impact behaviour; B. fracture toughness.

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INTRODUCTION

The present study, uses the experimental data from a published work1 [Wechsler et al., 2011] relating to the composite materials using the macadamia shell, pine cone and eucalyptus capsule as alternative fillers (referred to as the seed-coat-fibres (SCF)) to the wood-fibre (WF) in recycled polypropylene (PP) matrix for use in furniture towards better utilization of the food, agricultural by-products and waste plastics that would otherwise be sent to landfills.We focus on deriving advanced mechanical properties of the SCF-PP composites, SCFs and the radiata pine WF-PP composite.

1. Composite Manufacturing

The sample preparation as detailed by Wechsler et al., [2011][1]: The ground fibres and the PP are mixed at 165°C at 75 rpm in a HaackePolydrive mixer for 5 minutes, first with PP for two minutes, and then with added fibres for 3 minutes. The mixed samples are then pressed in a water cooled hot platen press with a 20 cm by 20 cm platen capacity. Each batch is pressed using a temperature of 170 °C for 15 minutes, and then cooled while the samples are still under compression. The average target thickness of the samples was 3 mm. The densities of the panels varied from 891 to 1053 $kg.m^{-3}$.

1.1 Composite Formulations

Wechsler et al[1] chose the filler ratio, 60% based on the work of Klysov [2007] and Wolcott [2001].[2,3] Three different panel material combinations are made using PP matrix with macadamia shells (A), pine cones (B) and eucalyptus capsules filler (C), respectively. Table 1 shows the make-up of each of the five panels prepared.[1]

1.2 Experimental[1]

The density is measured using a Ludlum 4417 density profilometer. Modulus of elasticity (MOE) and the modulus of rupture (MOR) are measured according to (ASTM D790, ASTM, 2010b). Impact test is conducted as per ASTM D256 (ASTM, 2010a) on a 3mm by 3mm notched sample. The samples for each test were cut from the same panel. Dimensions of the samples: for Impact test: 70 x 10 x 3 mm; Bending test: 100 x 10 x 3 mm. All the tests were carried out at 25° C. [1]

Table 1: Ratio of raw material and recycled polypropylene (PP) used for panel manufacture[Wechsler et al.,[1]].

Panel type	Recycled polypropylene based panels		
	Filler	***Filler ratio (wt %)***	***PP ratio (wt %)***
A (seed coat fibre)	Macadamia shells	60	40
B	Pine cones	60	40
C	Eucalyptus capsules	60	40
D(wood fibre)	Radiata pine wood	60	40
E	N/A	0	100

2. RESULTS AND DISCUSSION

2.1 Mechanical Properties

The mechanical properties of the composites (Wechsler et al., 2011)[1] are shown in Figure 1 and Table. 2. The discontinuous fibres used by Wechsler et al., 2011 would have a randomly oriented reinforcement. [1] This would mean there is no preferential stress direction and/or there is a low stress/strain level in the composite (Ashby & Jones, 1980; Rong et al., 2001, Bledzki&Gassan, 1996).[4,5,6]

Table 2 Physical and mechanical properties of the composites[Wechsler et al[1]., 2011]

Panel type	Property			
	Density (kg/m^3)	Modulus of Rupture (MOR) (MPa)	Modulus of Elasticity (MOE) (GPa)	w, IZOD Impact Strength(kJ/m^2)
A	1022	19.4	1.9	1.5
B	990	21.1	1.6	1.5
C	1053	27.7	2.0	1.8
D	1049	39.5	2.9	2.9
E	891	60.9	1.6	2.9

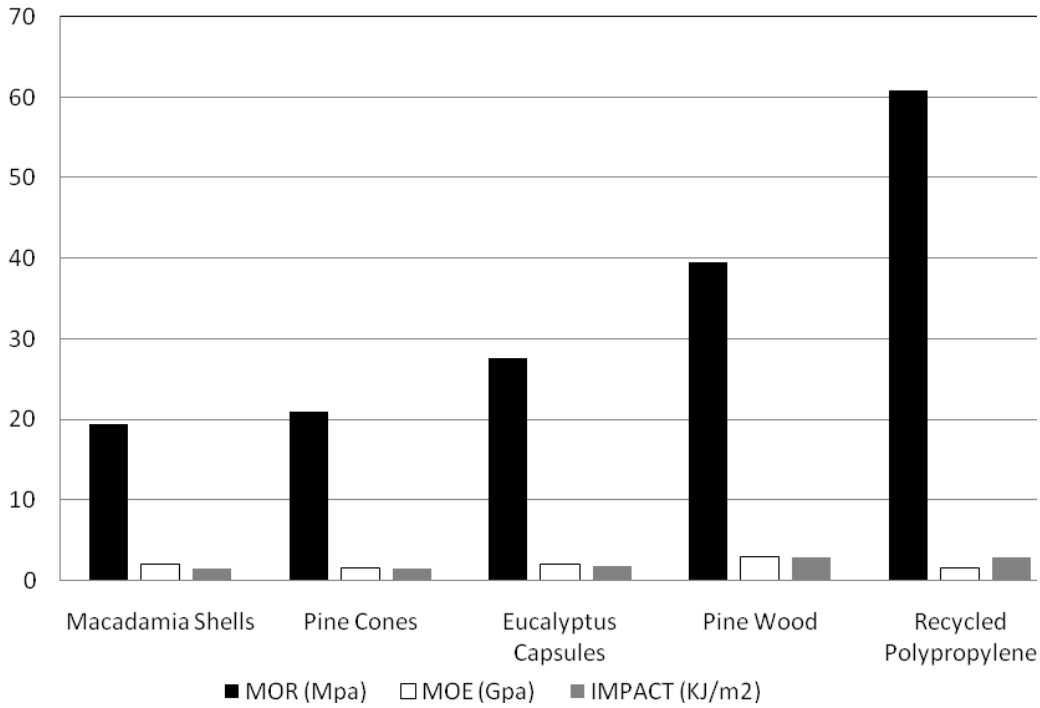

Figure 1. Mechanical properties of the composites [Wechsler et al., 2011]

In the present analysis, it is assumed that the fibre-particles are elastically isotropic with no preferential orientation. The following information is inferred from the tabulated values (Table 2):

- Unfilled PP showed lower MOE values than the filled PP. The average values of MOE of the SCF-PP and the WF-PP composites are higher than the unfilled PP.
- Increase in MOE in the composites is attributed to increased stiffness contributed by the WFs and the SCFs to the PP matrix.
- The WF - PP composite showed the highest modulus of 2.8 GPa, 30 % more than the SCF composites of macadamia shell and the eucalyptus capsule.

- The IZOD impact strength for the SCF – PP composites are lower than that of the WF-composites and the recycled PP, i.e. PP < PP-WF < PP-SCF.

The average MOR values of the SCF-composites are lower than the WF - composite and much lower than the flexure strength of the recycled PP, attributed to the stiffness contributed by the wood/SCFs. The high impact value of WF-PP composite indicates that it is tougher and less brittle than the SCF composites. Tough materials absorb more energy, whilst brittle materials tend to absorb less energy prior to fracture.

2.2 Deriving Gc, the critical strain energy release rate, K_{IC}, the fracture toughness:

The standard IZOD and Charpy tests are difficult to translate into engineering design (Paul and Bucknall, 2001] [7], partly because the impact strength is not a well-defined mechanical property as the modulus (Brown, 1973). [8]In material design it is important to know the Gc, K_{IC} and the MOEs -the material properties. Gc can be determined directly from the absorbed energy, w, from IZOD impact data, by extending, linear fracture mechanics theory, assuming elastic deformations (Marshall, et al., 1973., Brown, 1973., Fraser, and Ward, 1974., Plati and Williams, 1975).[8,9,10,11]IZOD's impact strength, is expressed as the specific fracture energy w/A, where w is the energy absorbed to break

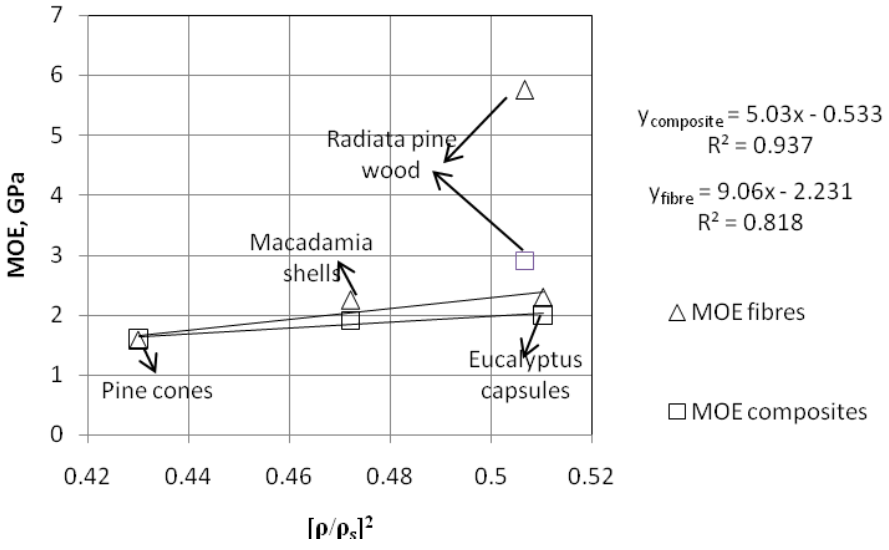

Figure 2. The Young's moduli of the fibres and their PP composites Vs the relative densities

the notched specimen and A is the cross-sectional area of the fractured ligament, determines the amount of energy absorbed in deforming and fracturing a standard specimen by impact loading causing a fast fracture to take place. Because of its strong geometry dependence it is not satisfactory in describing material property. It is assumed that all the impact energy goes into crack propagation, the energy lost by the pendulum in a notched impact test is solely the energy required to form the two new surfaces as the material breaks (Brown 1973). [8] The fracture may be either brittle or ductile or both.

Table 3 The Derived mechanical properties of the composites

Panel type	Gc, critical strain energy release rate, kJ/m^2	K_{IC} Fracture toughness $MPa.m^{0.5}$	σ estimated crack strength from K_{IC}(MPa)
A	2.60	2.25	24.16
B	2.60	2.03	21.80
C	3.08	2.46	26.41
D	4.93	3.77	40.42
E	4.91	2.82	30.25

The notched impact strengths quoted for polymers are the measure of the difficulty in initiating a moving crack Brown [1973].[8]Plati and Williams [1975] have related to Gc based on linear fracture mechanics theory as[11]:

$w = Gc.B.D.\emptyset$ 1

Where,

$$\emptyset = \frac{1}{2}\left(\frac{a}{D}\right) + \left(\frac{1}{36\pi}\right).\left(\frac{2L}{D}\right).\frac{1}{\left(\frac{a}{D}\right)} \quad \mathbf{2}$$

B = thickness of the specimen, D width of the specimen, L, the length of the specimen.

In the present study, $\emptyset$, the calibration function, is estimated to be equal to 0.58, based on the crack length, 'a' = 2.77 mm.

The K_{IC} for the composites is estimated from the Gc, using equation 3 (Irwin, 1964)[12]:

$$K_{IC} = \sqrt{EGc} \quad 3$$

Where, E = MOE of the composite.

The crack strength, σ, is obtained from equation 4:

$$\sigma = \frac{K_{ic}}{\sqrt{\pi a}} \quad \mathbf{4}$$

The calculated values of Gc, $K_{IC}$and σ are shown in Table 3

The σ (equation 4) is higher for the wood-fibre composites compared to the SCF composites. The σ and MOR values are similar (Table 2) for the WF and the SCF composites (Wechsler et al., 2011). [1] However the σ value of the PP is half the MOR (the ultimate strength), due to the brittle side of the transition of the "brittle-ductile" transition for PP, owing to the sharp notch tip and the high speed of the impact test (Brown 1973) with limited plastic deformation at the notch tip. [8]

Table 4 The derived mechanical properties of the fibres

fibres	Density Mgm^{-3}	Modulus of Elasticity (MOE) (GPa)	K_{IC} Fracture toughness ($MPa/m^{0.5}$)	σ crack strength (MPa)	Elastic anisotropy ρ_s/ρ
Macadamia shells	1.11	2.24	1.99	21.34	1.46
Pine cones	1.05	1.57	1.72	18.49	1.53
Eucalyptus capsules	1.16	2.29	2.28	24.42	1.40
Radiata Pine	1.15	5.76	4.81	51.56	1.41

The WFs and the SCFs-PP composites during the impact loading and flexure tests, undergo only brittle fracture hence show no variation in σ and the MOR values. The suppressed plastic deformation of the PP matrix in the composite is due to the high strain rate as well as the constraint imposed by the rigid wood/SCF. Similar impact fracture behaviour of several PP-WF composites exhibiting brittle fracture and nearly elastic behaviour (Hristov et al., [2004]; Brown [1973]]. [13,8]

Wechsler et al[1].,determined the mechanical properties of the matrix and the composites experimentally, but not the mechanical properties of the wood/SCFs perhaps due to the chopped up nature of the sample.[1]In this work we have derived the mechanical properties and the densities of the SCFs and WFs using the rules of mixtures, based on the assumption that a composite property is the volume weighted average of the phases (matrix and dispersed phase) properties using equation 5, Table 4, using the data in Table 2:

$$d_c = d_m * V_m + d_f * V_f \qquad 5$$

Where,
d_c =density of composites,
d_m = density of the matrix (PP)
d_f = density of fibre
V_f= volume fraction of WF = 0.61
V_m = volume fraction of matrix PP ($1-v_f$) = 0.39
V_m is calculated from the measured weight percentage, 60%, and the measured density, d_m of the PP[1] , (Table 1). The V_f was obtained as $1-V_m$.

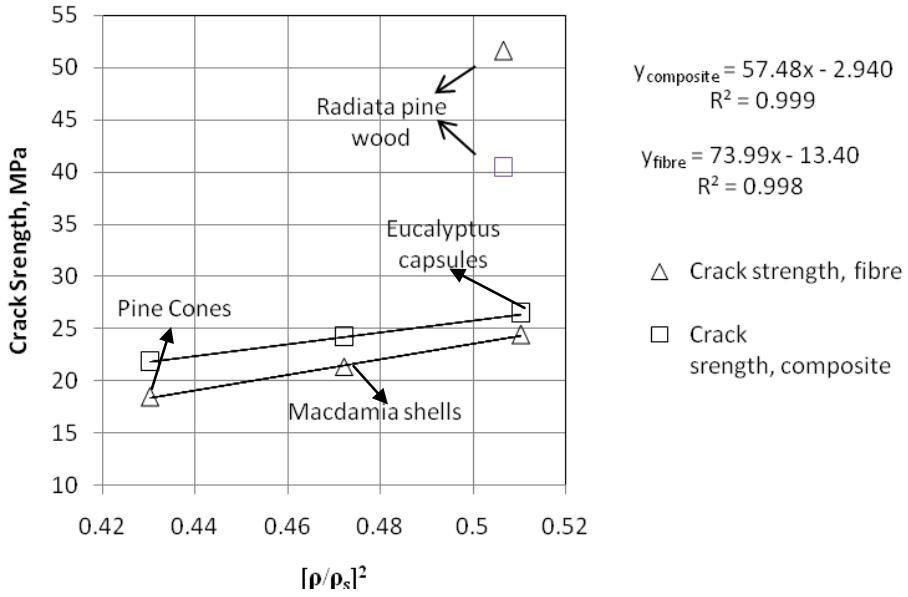

Figure 3. The crack strength of the fibres and their PP composites Vs their relative densities

For the discontinuous fibres (chopped) there are different models to predict the mechanical properties, MOE, tensile strengths, of the composites from the V_fs of the matrix and the fibres and the mechanical properties of the matrix and the fibres, which are effective only at certain V_f (Nielson, 1974., Cox, 1952., Loewenstein, 1966., Tsai and Pagano, 1968., Blumentritt and Cooper, 1975., Christensen and Waals, 1972., Lee, 1969., Pan, 1996., Lu, 2002) [14, 15,16,17,18, 19,20, 21,22] . We used Equation 6 to estimate the MOEs of the chopped fibres, assumed to be close to

the lower limits of the MOEs of the WF and the SCFs, from the measured MOEs of their respective PP-composites, based on the observation that the moduli of the particulate composites lie quite close to the lower value for the fibre-reinforced composites (Ashby & Jones, 1980) [4].

$$E_c = \frac{1}{\frac{V_f}{E_f} + \frac{(1-V_f)}{E_m}} \qquad 6$$

Where,
E_c = MOE of the composite;
E_f = MOE of the WF;
E_m = MOE of the matrix PP;
Using similar expression (equation 6), the lower limits of the fracture toughness, K_{IC}, and the tensile strength, σ, of the fibres were estimated from their respective PP-composites values, assumed to be equal to that of the chopped fibres.

The estimated MOEs of the fibres are higher than their PP composites. The obtained values in the present study are at the lower limit of the reported MOE values of the macadamia shells and much lower than the reported value for the WF. The reported MOE values for macadamia shells are 2 to 6 GPa (Jennings and Macmillan 1986) and between 4.2 to 5.2 GPa (Vincent, 1992).23,24 The MOE for the radiata pine WF is reported to be 10.2 GPa and the modulus of rupture ~80 MPa at 12% moisture content (Green, 2002) [25].

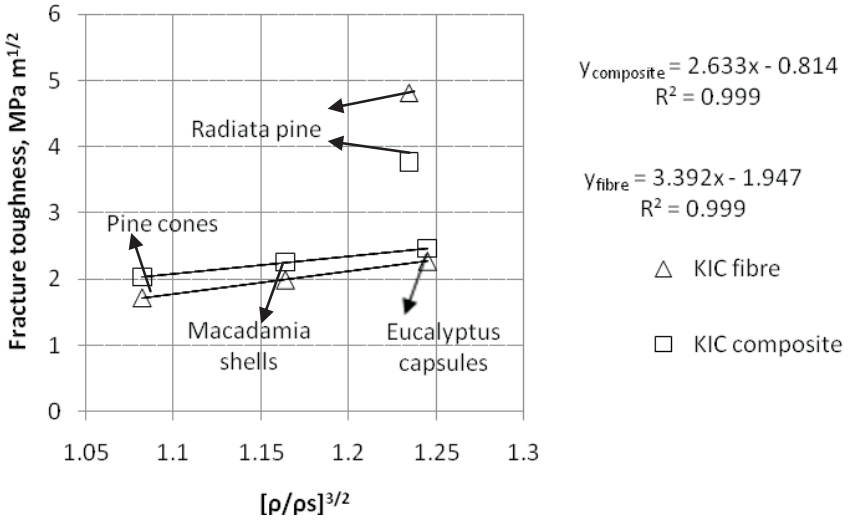

Figure 4. The fracture strength of the fibres and their PP composites Vs their relative densities

The estimated K_{IC} value for macadamia SCF, 1.99 MPa.$m^{0.5}$ isclose to thereported K_{IC} value for macadamia shells, 1-2 MPa.$m^{0.5}$(Jennings and Macmillan 1986).[23] The K_{IC}, and the σ of the SCFs are lower than the composites indicating that the addition of PP has increased their fracture toughness and the stress. However, KIC, and the σ of the WF are higher than the composites indicating that the addition of PP has decreased the fracture toughness and the stress of the WF. This is in conformity with the previous references that the reinforcement of PP by means of WFs, significantly reduce the composite toughness [Woodhams, et al., 1984.,Kokta, et al., 1983]. [26,27]

Table 5 The specific strengths of the fibres and the fibre-PP composites

Material	E/ρ fibre	E/ρ composite	σ/ ρ fibre	σ/ ρ composite	k_{IC}/ρ fibre	k_{IC}/ρ composite
Macadamia shells	2.03	1.86	19.33	23.64	1.80	2.20
Pine cones	1.50	1.62	17.54	22.03	1.64	2.05
Eucalyptus capsules	2.00	1.90	21.11	25.09	1.97	2.34
Radiata Pine	5.01	2.77	44.82	38.53	4.18	3.59
Polypropylene	1.82		33.95		3.17	

The MOE, the K_{IC}, and the σ of the WFs and the SCFs depend on the density, composition and the fibre orientation contributed by the tracheids (Ashby and Jones 1988) [28]. In WFs, the crystalline cellulose microfibrils account for 45 % of the cell-wall, contributing to the strength and the modulus of the fibres. The cellulose chains are arranged parallel to each other, linked by hydrogen bonds, and linked with amorphous hemicelluloses and lignin which confer stiffness to fibre called microfibrils (Cristaldi et al., 2010).[29] Lignin, imparts great strength and hardness to the wood (Armstrong, 2010), [30] assisting and strengthening the attachment of hemicelluloses to microfibrils. While cellulose is crystalline, strong, and resistant to hydrolysis, hemicellulose is amorphous with little strength. Microfibrils are cross-linked together by hemicelluloses homopolymers.

The weight of WFs/SCFs is due to the cellulose and lignin in the cell-walls around the billions of individual cells. The cell water material has a specific gravity of about 1.5 and is heavier than water. In general, the tensile strength of the fibres increases with increasing cellulose content and with decreasing angle of helix axis of the fibres. The modulus of the WF/SCF is that of the cell-wall scaled down by the fraction of the section occupied by the cell-wall. If the density of the section occupied by the cell-wall is doubled, the modulus doubles. The extractives content in the wood also influences the density of the fillers (Gutierrez and Baonza, 2009).[31]Thus even though the WFs/SCFs are composed of similar materials, the differences in their properties are attributed to the differences in their relative densities, $\frac{\rho}{\rho_s}$, where, ρ is the density of the WF/SCF and ρ_s is the density of the cell-wall. For the fibre reinforced composites, the MOEs vary as equation 7, when loaded along the grain (Ashby & Jones 1988). [28]

$$E_{f(axial)} = E_s \left[\frac{\rho}{\rho_s}\right] \quad \textbf{7}$$

The transverse modulus of the fibre (assumed for the discontinuous fibres) is given by equation 8.

$$E_f(trans) = E_s \left[\frac{\rho}{\rho_s}\right]^2 \quad \textbf{8}$$

Similar trend is expected for σ and K_{IC} (equation 9 and 10):

$$\sigma_{(trans)} = \sigma_s \left[\frac{\rho}{\rho_s}\right]^2 \quad \textbf{9}$$

$$K_{IC(trans)} = K_{ICs} \left[\frac{\rho}{\rho_s}\right]^{3/2} \quad \textbf{10}$$

Where, the subscript, s denotes the property of the cell-wall, e.g., E_s is the modulus of the cell-wall.

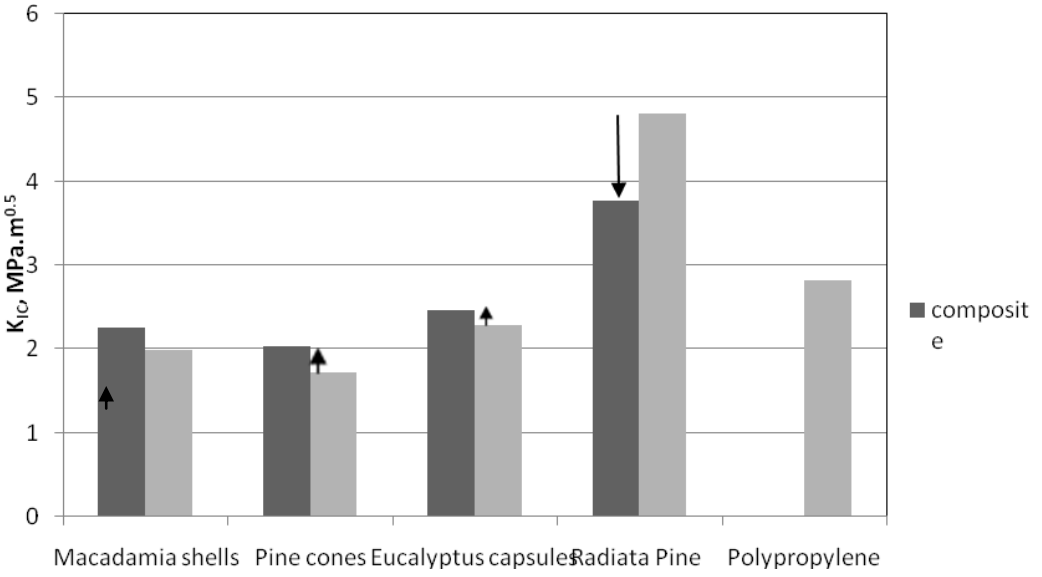

Figure 5. Change in KICs of the composites of the wood fibres and seed coat fibres

2.3 Correlation between the density and the mechanical properties of the discontinuous WFs/SCFs and their respective PP-composites

To study the effect of relative density/density of the fibres on the mechanical properties of the fibres and the composites, the MOEs, and σ of the fibres and the composites are plotted against the $[\rho/\rho_s]^2$,where,$[\rho/\rho_s]$ is the relative density. K_{IC} was plotted against $[\rho/\rho_s]^{3/2}$, in accordance with equation 10. Based on the water content of the fibres at ~3%, the density of the cell-wall is estimated to be ~1.6 Mgm^{-3}(Ashby and Jones 1988). [28]

Figure 2 shows the plots of MOEs of the fibres and their PP- composites vs $[\rho/\rho_s]^2$. The E_S value, ~9 GPa for the cell-wall, obtained from the slope of the MOE vs $[\rho/\rho_s]^2$ plot for the SCF is similar to the transverse cell-wall modulus, 10.77 GPa, at 3 % moisture (Table 4) (10 GPa at 10 % moisture -Ashby & Jones, 1988)[28] While the MOEs of the SCFs show similar trend, the WF deviates. The slope values indicate that the MOEs of the composites show less dependence on the $[\rho/\rho_s]^2$, compared to the fibres. This is understandable since the PP content in composites is less likely to depend on the $[\rho/\rho_s]^2$.

Figure 3 shows linear trend for the plot, σ of the SCFs – PP composites vs the $[\rho/\rho_s]^2$. The obtained strength, σ_s value ~ 74 MPa for the cell-wall, from the slope of the plot is higher than the transverse cell-wall yield strength, 50 MPa (Ashby &Jones, 1988). [28]While the σ values of the SCFs show similar trend, the WF deviates significantly. The slope values indicate that the σ values of the composites show less dependence on the $[\rho/\rho_s]^2$, than the fibres.

Figure 4 shows linear trend for the fracture toughness, K_{IC} of the SCFs and the composites Vs the $[\rho/\rho_s]^{3/2}$. While the K_{IC} values of the SCFs show similar trend, the WF deviates significantly. The slope values indicate that the K_{IC} values of the composites show less dependence on the $[\rho/\rho s]^2$, compared to the fibres.

While the MOEs, K_{IC}s and σ of the SCFs and their PP composites showed a linear trend, the values for WFs deviated from linearity showing higher values than the SCFs. The deviation in MOE for WF –PP composite compared to the SCF-PP composites was considerably less showing almost a similar trend.Figures 2-4 clearly show how the density of the WF affects the mechanical properties of the fibres and their PP composites.

To summarise:

- Mechanical properties of the WF-PP composites are inferior to that of the WFs,
- Mechanical properties of the composites of PP-SCFs are superior to that of the SCFs (Figures 5 and 6).

2.4 Elastic anisotropy vs density

The elastic anisotropy of the fibres [ρ_s/ρ], (Table 4) increases as the density decreases. Thus pine cone SCF exhibits the highest anisotropy while the eucalyptus SCF and the radiata pine WF showed the least anisotropy values. The anisotropy values followed the trend: Macadamia SCF > Pinecone SCF > eucalyptus SCF > radiate pine WF.

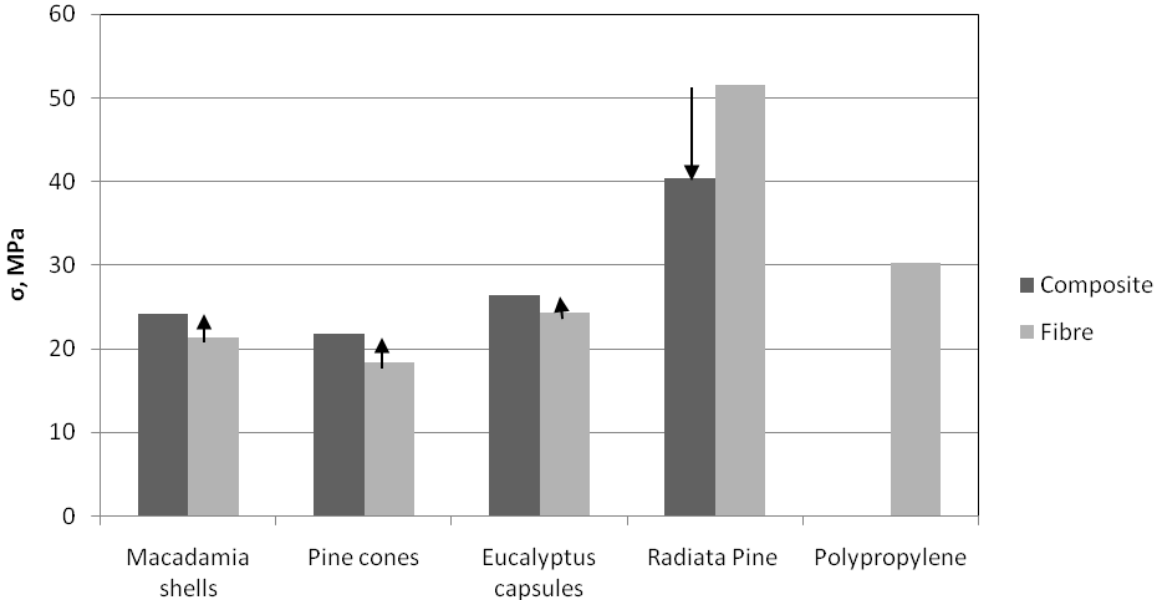

Figure 6. Change in crack strengths of the composites of the wood fibres and seed coat fibres

2.5 Specific strengths

The specific strengths of the fibres and the fibre-PP composites, the properties per unit weight, enable to compare the strengths of different engineering materials (Table 5). The specific strengths of the SCFs of macadamia, eucalyptus, and the pine cones are lower than the pine radiate WFs.It is inferred that the mechanical behaviours of different fibres/composites are influenced by: chemical composition of the cell-wall, hence the density/relative density of the wood/SCFs; dispersion of the wood/SCFs in the PP matrix; V_f of fibres in PP matrix; the hydrophilic nature of the wood/SCFs and the hydrophobic matrix polymers, and the processing temperature.

Table 6. Composition of wood fibres used in Wechsler et al., 2011

Panel type	Macadamia shells (Toles et al., 1998)	Pine cones (Ayrilmis, et al., 2009., Buyuksari, et al., Duman, et al., 2009)	Radiata Pine (Johnsson and Packer)
Fibres: Cellulose %	25	32.7	42
Matrix: Lignin %	47	24.9	29
Hemicellulose %		37.6	7
Water	11		
Extractives %		4.8	

2.6. Effect of wood composition on the mechanical properties

2.6.1 Cellulose, lignin

The composition of the wood/SCFs is shown in Table 6. Basic composition of the wood cell-wall is as shown in Table 7. It is seen that the cellulose content of the radiata pine WF at 42 % is similar to that of the other woods, whereas the SCFs showed much lower cellulose content. The MOE of the cellulose is high (25-40 GPa) due partially to its crystallinity, lignin, the amorphous polymer has much less MOE of 2 GPa.

Even though macadamia shell SCFs have higher amounts of lignin, a binder, they have much lower amounts of cellulose content than the pine cones (Ayrilmis, et al., 2009) - yet exhibiting similar mechanical and physical properties to the pine cones (Table 4).[32] The macadamia shell SCFs are not expected to show high tensile strength or MOE due to their higher lignin content than cellulose.

Lignin content decreases the tensile strength/index before homogenisation. However after homogenisation, the tensile index, elastic modulus and toughness can increase with increasing lignin content (Spence et al., 2010).[33]

2.7 Effect of processing temperature on the mechanical properties

The composites were processed at ~170° C by Wechsler et al., 2011. [1] At this temperature the WFs/SCFs develop visco-elastic properties. The cell-wall-lignin has a glass transition temperature 115° C allowing the fibres to soften, deform and peel generating fibrils (Fernando et al., 2007).[34] The processing temperature (~170 ° C) being higher than the glass transition temperature of the lignin (115° C), the softened lignins preferentially bind with the other wood/SCFs in the matrix leading to increased fibre-fibre interaction and clustering rather than presenting a well dispersed phase in the PP matrix. This could detrimentally affect the mechanical properties of the composites.

2.8 Filler dispersion

Lack of dispersion of fillers in PP can be overcome using the dispersion agents and proper mixing (Wolcott and Englund, 2009). [35]In determining the mechanical properties of the composites of WF-plastics, the most serious concern is their hydrophilic nature due to the presence of pendant hydroxyl and polar groups in various constituents, leading to poor adhesion between fibres and hydrophobic polymer matrix (Rong et al., 2001, Bledzki&Gassan, 1996). [5,6] In Wechsler et al., 2011's study[1], absence of coupling agents or surface activation methods to promote adhesion, limit the interfacial adhesion between the polar wood and the non-polar thermoplastics. However, it is expected that molecular adhesion due to van der Waals attraction is present in these composites. Such attractions are reported between hydrophilic cellulose and hydrophobic polystyrene by Gamstedt et al., 2011.[36]

Table 7. Composition of cell wall of wood (Ashby & Jones, 1988)

Material	Structure	Approxwt %
Fibres: Cellulose	Crystalline	45
Matrix:		
Lignin	Amorphous	20
Hemicellulose	Semi-crystalline	20
water	Dissolved in matrix	10
Extractives	Dispersed in matrix	5

PP and the cellulose can be in close contact through a hydrophobic interaction due to the packing arrangement of the cellulose chains [Zugenmaier, 2006] [37]. The hydrophilic part of the cellulose chain is compensated by hydrogen bonds interconnecting the flat cellulose molecules edge on, forming sheets with hydrophobic surfaces which also cover the surface of the cellulose crystallites and fibres and are responsible for the hydrophobic interaction with the PP molecules.

Natural fibres due to their surface roughness exhibit interfacial strength owing to mechanical interlocking, improving the transverse properties (Rong et al., 2001., Bledzki and Gassan, 1996). [5,6] Pine cones and eucalyptus SCFs are more porous than macadamia shells, which could assist in enhanced mechanical interlocking improving

their mechanical properties.The improvement/deterioration in the mechanical properties of the composites compared to the SCF/WFs is indicative of the fibre-PP interaction either due to molecular adhesion or the mechanical locking.

2.9 Fibre-volume/weight fraction:

The plastic /or the WF/SCF content affect the mechanical properties of the composites. Baxter [1992][38] studied the strength of metal matrix reinforced with randomly oriented discontinuous graphite fibres. He found significant strength reduction as the fibre V_f become higher, and if the interfacial bond is weaker than the matrix, then the strength of the randomly oriented composites increased only modestly or not at all with the increased fibre V_f. For V_f higher than 0.3, imperfections in the composite such as clustering or spaces between fibres, not infiltrated by the matrix served as debilitating micro-cracks.

A decrease in strength was observed by Li and Mai [2000][39] as the fibre weight fraction increased from 0.20 to 0.30 due to the fibre-fibre interaction at high V_f leading to poor dispersion of fibres. Similar phenomena were observed on the mechanical properties of wood flake/polyethylene composites by Balasuriya et al., [2001].[40]The deduction in strength was attributed to the increased interactions between flakes that resisted uniform dispersion of the flakes in polyethylene matrix. Random orientation of the WF became difficult to achieve as the V_f of the fibres increased [Manera ,1977]. [41]

Wechsler et al., [1] have kept the V_f, at ~0.6, constant, hence the effect of varying the V_f is not known. [1] At a lower V_f, the SCFs may be expected to show better dispersion leading to improved mechanical properties. However, the wood-fibres may not show improved mechanical properties at lower V_f as seen from Figures 6 and 7, where the mechanical properties of the WF-PP composites are inferior to the WFs.

3. CONCLUSIONS

This study has considered the data used in the study, Wechsler et al., 2011 of agricultural crop by-products for potential use in composite material panel fabrication. [1] We have derived advanced mechanical properties of the three new SCFs, viz, macadamia shells, pine cones and eucalyptus capsules and the radiata pine WFs and their respective composites with PP.

The mechanical behaviours of different fibres/composites are influenced by: chemical composition of the cell-wall, hence the density/relative density of the wood/SCFs; dispersion of the wood/SCFs in the PP matrix; V_f of fibres in PP matrix; the hydrophilic nature of the wood/SCFs and the hydrophobic matrix polymers, and the processing temperature.

The relative density, relating to the chemical composition, in particular high cellulose content influences greatly the difference in their properties, with WF exhibiting better mechanical properties than the SCFs. The mechanical properties of the WFs and the SCFs and their PP composites showed linear correlation to the relative densities of the WF and the SCFs.

The radiata pine WF has the best performance in a polypropylene matrix, followed by, the SCFs. The WFs showed better mechanical properties than the WF composites as also reported in the literature. However, composites of the SCFs showed better mechanical properties than the SCFs.

Radiata pine WF has the best mechanical performance in a PP matrix, followed by the SCFs of eucalyptus capsules, macadamia shells, and the pine cones. The specific strengths of the SCFs of macadamia shells, eucalyptus capsules, and pine cones are lower than the radiata pine WF. The gap between the mechanical behavior of the WF composite and the SCF composite is narrower compared to that of the WFs and the SCFs. The material properties Gc, and K_{IC} indicated a fast brittle fracture of these composites.

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