APPLICATION OF MICROMECHANICAL MODELS FOR ESTIMATING WOOD PLASTIC COMPOSITES PROPERTIES

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ABSTRACT

The application of micromechanical models for the estimation of the properties of polymer matrix composites is known for a long time, for example several successful attempts were carried out for glass fibre reinforced composites. Due to the increasing market for Wood Plastic Composites (WPC) and the increasing research attention for these materials over the last years, this work aims to correlate the tested material properties with the parameters of the formulation, e.g. particle size and wood content, by means of rule-of-mixture type models, which account for cylindrical fibres as well as spherical particles, respectively.

We found a good correlation between the results from mechanical testing of the composites and the estimations with both models applied, but with some constraints regarding the geometry of the wood particles, especially in the case of the model based on spherical geometry.

1. INTRODUCTION

Estimating the properties of polymer matrix composites with micromechanical models is known for a long time. The model originally developed by Kelly and Tyson for metal matrix composites was successfully applied to glass fibre reinforced polymers like polypropylene and polyamide in the past [1,2].

Due to the increasing market for Wood Plastic Composites (WPC) and the increasing research attention for these materials over the last years, this work aims to correlate the material properties with the parameters of the formulation, e.g. particle size and wood content, by means of rule-of-mixture type models. Two models were investigated for their applicability. The first is the model accounts for cylindrical fibres (developed by Kelly and Tyson) and the ultimate strength of fibre reinforced composites [3, 4]. The second model is an approach for particulate reinforced, applied for glass beads in a polyester matrix [5]. These models are described below.

For the description of the ultimate tensile strength of the composites, we used a Kelly-Tyson-Model approach as the basis of our considerations (Eq. 1).

$$\sigma_C = \tau_c \frac{l}{d} V_f + \sigma_m' (1-V_f) \qquad (1)$$

where σ_C is the ultimate composite strength, τ_c is the interfacial shear strength, l and d are particle length and diameter, respectively, V_f is the fibre volume fraction and σ_m' is the ultimate tensile strength of the matrix. This model only account for subcritical fibres and also states that the fibres are all aligned in the direction of load.

We modified this model, to get better applicability due to particle orientation and particle packing at higher volume fractions (Eq. 2).

$$\sigma_C = \eta_0 \tau_c \frac{4l}{d} V_f (1-V_f^3) + \sigma_m' (1-V_f) \qquad (2)$$

where the parameters are the same as mentioned above, meaning η_0 is an orientation factor, and the factor $(1-V_f^3)$ is an inverse probability of touching between the wood particles. The origin of the factor 4 is not completely clear until yet, but we found this factor necessary to yield appropriate data when estimating the composite properties, as reported in one of our previous works [6].

The second approach for the description of the ultimate composite strength is shown in Eq. 3. It was developed starting from the Kelly-Tyson-approach, to account for spherical particles in a polymer matrix composite [5].

$$\sigma_{uc,b} = 0.83\ \tau_c V_f + K \sigma_{um} (1-V_f) \qquad (3)$$

where $\sigma_{uc,b}$ is the ultimate tensile strength of the composite, τ_c the interfacial shear strength, V_f the fibre volume fraction, σ_{um} is the ultimate tensile strength of the matrix and K is a factor accounting for the relative change of strength due to the presence of the spherical filler. The factor of 0.83 (which is also referred to as factor a) results from considerations regarding the interface between a bead and the matrix, as shown in literature.

2. EXPERIMENTAL

Raw materials used in this study were wood particles with different particle sizes, namely a non-commercial spruce wood, which was sieved to yield different fractions between 0.125 – 2 mm sieve width, wood particles type BK40/90 which is referred to as coarse needlewood and type CW630PU, which is referred to as fine needlewood. Both wood types were supplied by *J. Rettenmaier and Sons*. Further, a polypropylene (PP) homopolymer (MFR at 230°C and 2.16 kg = 8 g/10 min, *Borealis*) as well as in some formulations maleic anhydride grafted polypropylene (MAH-PP, *Exxon Mobile Chemicals*) as a compatibilizer were used.

The composites were produced by compounding the wood particles into polypropylene by means of a co-rotating twin screw extruder (*Thermo Prism* TSE24HC) and after a drying step at 80°C for 4 h subsequent injection moulding with an injection moulding machine (*Engel* ES80) to retrieve universal test specimens, according to ISO-3167.

Tensile strength was tested using a universal testing machine (*Zwick-Roell* Z020), according to ISO-527 with a crosshead speed 2 mm/min until the break of the samples.

For the evaluation of particle geometry after processing, the sample was extracted in boiling xylene [7] under reflux for about three hours. The hot solution was vacuum filtered to regain the wood particles, which were dried and scanned for their length and width by means of a light microscope (*Olympus* BX61) and the according image analysis software (*AnalySIS Five*). From these results the length weighted lengths and widths were calculated for further evaluation.

To measure the wood particle orientation, thin sections were cut from the test specimen with a microtome (*Leica* RM2255). These thin sections were investigated with the microscope for the tilting angle of the wood particles in regard to the main axis.

3. RESULTS AND DISCUSSION

The results of the particle orientation measurements are shown in Figure 1. The fibre orientation factor is calculated as $\eta_0 = \cos^2\varphi$, where φ is the average tilting angle measured with the microscopic method above. The composites used for this analysis were the ones with the different spruce particles, due to the fact that they all show comparable aspect ratios. As we can see, with decreasing particle size we get increasing orientation in the injection moulded universal test specimen. This seems to be logical, because smaller particles will not interact that much while filling the mould and therefore are aligned more in the main direction of the universal test specimen. For the composites containing the needlewood we chose the orientation factor after determining the actual particle size of the wood particles in the composites based on this dataset.

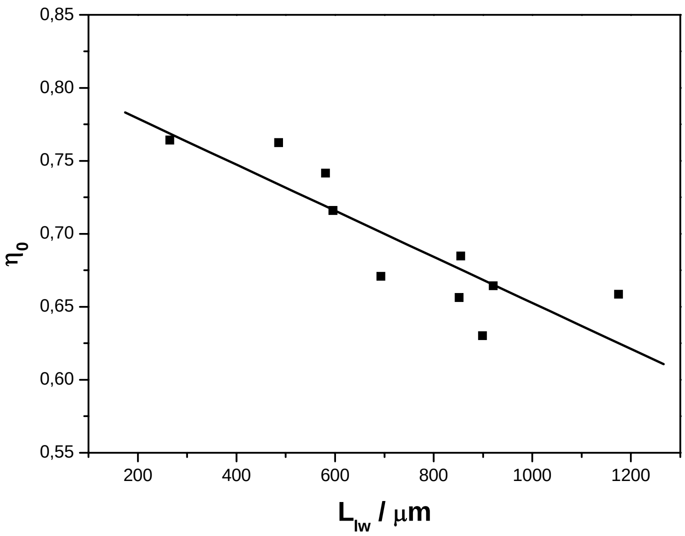

Figure 1: Orientation factor vs. length weighted length of wood particles for wood plastic composites containing 30wt% of wood

Table 1: Dataset used for the estimation of different wood plastic composites

		η_0	τ_c [MPa]	l/d	V_f	σ_m' [MPa]	σ_c[1] [MPa]	σ_c[2] [MPa]	s[3] [MPa]
spruce wood	0wt% MAH-PP	0,63	2.2	1,9	0,2236	30	27,0	26,47	0,15
		0,66		2,1	0,2075		27,5	27,15	0,18
		0,68		1,8	0,2252		26,8	26,07	0,24
		0,67		1,9	0,2366		26,9	26,54	0,41
		0,72		2,1	0,2413		27,1	27,35	0,18
		0,74		2,4	0,2400		27,8	27,86	0,08
		0,76		2,2	0,2281		27,6	28,34	0,16
		0,76		2,4	0,2138		28,1	29,22	0,20
fine needlewood		0,75	3.5	1,9	0,2128	30	27,8	28,28	0,19
					0,2919		26,9	28,49	0,38
					0,4001		25,5	26,66	0,16
					0,5031		23,7	23,9	0,19
					0,6119		21,1	19,24	0,28
coarse needlewood		0.73	3	2,3	0,2024	30	27,9	28,74	0,14
				2,4	0,3006		27,0	27,36	0,08
				2,1	0,4000		24,9	25,7	0,16
				2,1	0,5013		22,9	23,01	0,45
				2,2	0,6034		20,9	20,07	0,09
	2wt% MAH-PP	0.73	6	2,0	0,2633	30	31,2	32,39	0,09
					0,3787		31,2	32,44	0,13
					0,4718		30,6	33,92	0,32
					0,7458		22,9	28,39	2,19

[1] … calculated composite tensile strength,
[2] … measured composite tensile strength,
[3] … standard deviation of measured data

When estimating the composite strength with the model in Eq. 2, we find very good accordance for the different particle sizes and volume fractions (Fig. 2). The error between the estimation and the measured data is in the region below 10% for the most cases, which we find very satisfying thinking of the fact that we deal with natural products in this case.

The dataset used for that are listed in Table 1. The damping factor of $(1-V_f^3)$ accounts very well for the loss of properties at higher wood contents. Also with the presence of a compatibilizer, the model fits the test results very well. The only difference between the fits for the coarse needlewood is the interfacial shear strength τ_c, which equals 3 MPa for the wood plastic composites without and 5.5 MPa for the wood plastic composites with 2wt% compatibilizer. The interfacial shear strength between 2.2 – 3.5 MPa, which is found for the composites without compatibilizer, is in very good accordance with data found in literature. Rogers et *al.* [8] reported 1.5 – 3 MPa for the system pine – polypropylene, which was measured via dowel pull out tests.

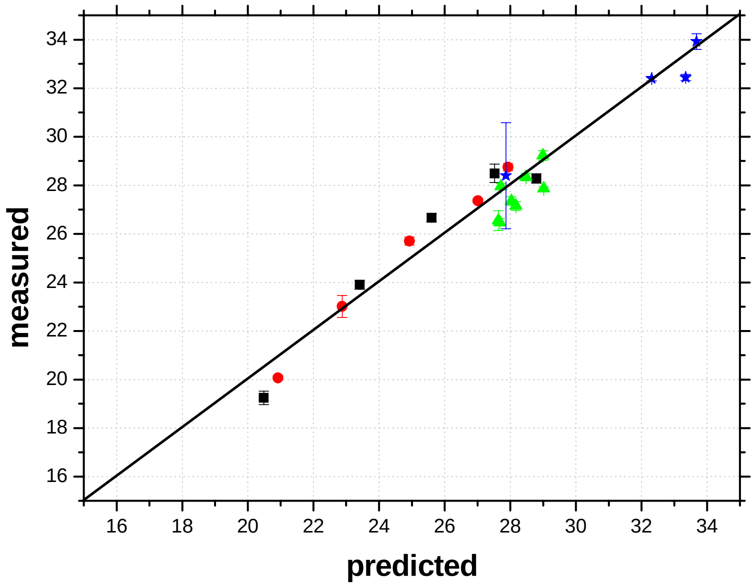

Figure 2: Measured vs. predicted tensile strength for different wood plastic composites; ▲ … spruce wood, ● … fine needlewood, ■ … coarse needlewood, ★ … coarse needlewood with compatibilizer

In case of the application of the model for spherical fillers (Eq. 3), we tried to fit the model to the measured data with variations in the parameters a and K only. This was done due the fact, that there are no reference data found for wood plastic composites in the literature, and in the first step we wanted to check if the model is applicable anyways. We found that the fibre volume fraction V_f shows the greatest influence, and for the dataset with the different spruce wood particles, we had to modify the value of K for every single composite. Due to this, we did not test this model any further for the different wood particle sizes. However, we wanted to see if it is possible to fit a dataset with the same particle geometry, but variations in fibre volume fraction. With the interfacial shear strength τ_c = 3 MPa and the matrix strength σ_m = 30 MPa (the same as applied for the estimations above), we yield a = 4.15 and K = 1.15 (Fig. 3). When comparing this data to the one reported in the article from Leidner and Woodhams [5], we find huge differences. First, the value of K should be smaller than one (regardless if there is adhesion at the interface or not), which it is not in our case. Second, we find a value of a = 4.15 vs. a = 0.83 reported for spherical particles. This is in our opinion due to the fact that the wood particles are more ellipsoid than ball-shaped.

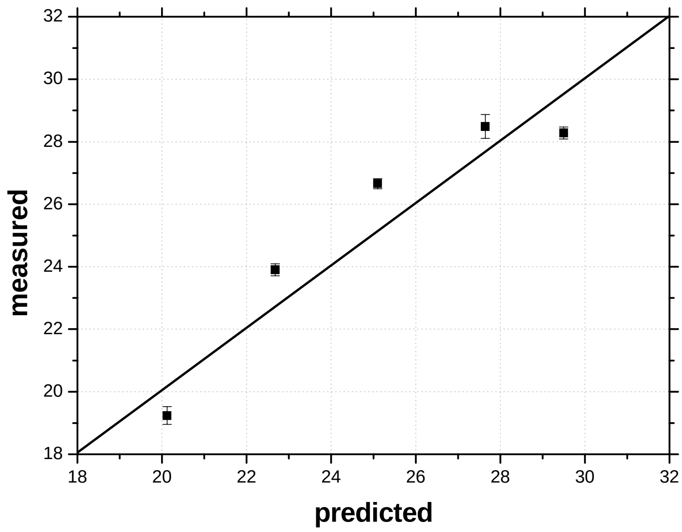

Figure 3: Measured vs. predicted tensile strength for wood plastic composites containing fine needlewood with the model based on particulate fillers

4. CONCLUSIONS

In conclusion, both models are applicable for wood plastic composites in principle, but with some constraints. For the Kelly-Tyson-Model we find a factor of 4, which is not completely explainable within this theory. We suspect that this factor is connected with the wood particle geometry somehow, but this has to be investigated in the future.

On the other hand, for the model basing on the spherical particles, we find different K values for the same particle geometry at different wood contents, as well as huge differences in the factors accounting for the geometry. We think that these constraints occur due to the shape of the wood particles, which are neither cylindrical nor spherical, but a kind of irregular mixture of both geometries. Further, we think that the modified Kelly-Tyson-Model, basing on the cylindrical geometry fits better to the wood particles, although they show very low aspect ratios, than the model based on the spherical geometry.

Concluding this work, we think that application of the Kelly-Tyson-Model for estimating composite strength is possible with good results, but is very labour intense, because of the need to measure the different parameters, like orientation, particle geometry present in the composite, and interfacial shear strength. Nevertheless these estimations can reduce cost and labour for developing basic formulations for future application of wood plastic composites.

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