VOLUMETRIC INTERACTION MODEL IN NATURAL FIBER COMPOSITES – A CONCEPT TO BE USED IN DESIGN AND PROCESS OPTIMIZATION OF COMPOSITES

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Abstract

Natural fiber composites contain typically a relative large amount of porosity, which considerably influences properties and performance of the composites. The large porosity must be integrated in the conversion of weight fractions into volume fractions of the fiber and matrix parts. A model is presented to predict the volumetric composition, as well as the density of composites as a function of the fiber weight fraction. The model predicts two cases of composite volumetric interaction separated by a transition fiber weight fraction, at which the combination of a high fiber volume fraction, a low porosity and a high composite density is optimal. It is demonstrated that the model provides a concept to be used in design and process optimization of natural fiber composites.

1 Introduction

Most properties of composite materials are directly governed by the content of the three constituent volume parts: fibers, matrix and porosity. The mutual interaction between these three parts is called volumetric interaction. In the case of a low (and negligible) porosity content, as is most often the case in synthetic fiber composites, the volume fractions of fibres, matrix and porosity (V_f, V_m and V_p) can be calculated from the fiber weight fraction (W_f):

$$V_{f*} = \frac{W_f \rho_m}{W_f \rho_m + (1 - W_f)\rho_f}$$

$$V_{m*} = 1 - V_{f*} \qquad (1, 2, 3)$$

$$V_p = 1 - (V_{f*} + V_{m*}) = 0$$

where ρ_f and ρ_m are density of fibers and matrix, respectively, and the asterisk (*) specifies the situation of no porosity in the composites. However, if the porosity content is high (and not negligible), as is most often the case in natural fiber composites, the porosity content must be integrated into the calculations. Table 1 shows a typical example of volumetric composition in natural fiber composites with variable fiber weight fraction.

Table 1. Volume fractions of fibers, matrix and porosity in jute fiber/polypropylene composites with variable fiber weight fraction [1].

Fiber weight fraction	Volume fraction Fibres	Matrix	Porosity
0.346	0.229	0.723	0.048
0.354	0.237	0.724	0.039
0.359	0.238	0.712	0.051
0.387	0.258	0.683	0.059
0.432	0.291	0.641	0.068
0.452	0.295	0.598	0.108
0.475	0.322	0.595	0.083
0.509	0.330	0.531	0.140
0.547	0.337	0.466	0.197

This paper presents a model for predicting the volumetric interaction in composites. Specifically, based on a number of empirical parameters, the model predicts the porosity as a function of the fiber weight fraction, and calculates the related fiber and matrix volume fractions. The model provides also predictions of composite density, which is an isotropic materials property, used as a selection criterion for nearly all engineering materials. The model applies to composites in general, but is in particular relevant to composites with high porosity content, such as natural fiber composites. It will be demonstrated how the model can be used in design and process optimization of composites.

2 Presentation of volumetric interaction model

Fig. 1 shows a schematic illustration of the constituent volumes in a composite system with discrete fibers embedded in a continuous matrix, and with a spatial distribution of porosities. The volume fractions of fibers and matrix are related to the total composite volume, and these variables cannot be established without knowledge of the amount of the third volume-based part in composites, the porosity. Thus, the volume fractions of fibers, matrix and porosity are mutually dependent variables. The fiber weight fraction, W_f, will be used as the basic independent variable. A detailed development of the model is presented in a recently published paper by Madsen et al. [2].

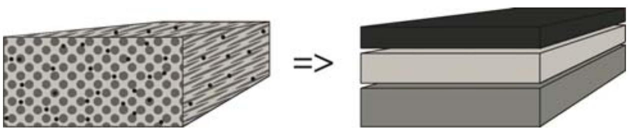

Fig. 1. Schematic illustration of the three constituent volumes of fibers (medium gray), matrix (light gray) and porosity (black) in a composite material, and the representation by slabs of volumes used in the model.

The model predicts two cases of composite volumetric interaction: Case A and B. In Case A, where the fiber weight fraction is below a transition value, $W_{f\,trans}$, the volume fractions of fibers, matrix and porosity are governed by the density of fibers and matrix, and a number of porosity constants ($\alpha_{pf(i)}$ and $\alpha_{pm(i)}$) that can be evaluated from the microstructure of the composites [2]:

$$V_f = \frac{W_f \rho_m}{W_f \rho_m \left(1 + \sum \alpha_{pf(i)}\right) + \left(1 - W_f\right)\rho_f \left(1 + \sum \alpha_{pm(i)}\right)}$$

$$V_m = \frac{\left(1 - W_f\right)\rho_f}{W_f \rho_m \left(1 + \sum \alpha_{pf(i)}\right) + \left(1 - W_f\right)\rho_f \left(1 + \sum \alpha_{pm(i)}\right)}$$

$$V_p = 1 - \left(V_f + V_m\right)$$

$$\rho_c = \frac{\rho_m \rho_f}{W_f \rho_m \left(1 + \sum \alpha_{pf(i)}\right) + \left(1 - W_f\right)\rho_f \left(1 + \sum \alpha_{pm(i)}\right)}$$

(4, 5, 6, 7)

In Case B, corresponding to insufficient matrix, the fiber weight fraction is above the transition value, $W_{f\,trans}$. The fiber assembly is fully compacted to its minimum volume (under the operating process conditions), which means that the volumetric interaction is constrained by a maximum obtainable fiber volume fraction, $V_{f\,max}$:

$$V_f = V_{f\,max}$$

$$V_m = V_{f\,max} \frac{\left(1 - W_f\right)\rho_f}{W_f \rho_m}$$

(8, 9, 10, 11)

$$V_p = 1 - \left(V_f + V_m\right)$$

$$\rho_c = \frac{V_{f\,max}}{W_f}\rho_f$$

3 Model validation

Fig. 2 shows an example of the good agreement between model predictions and experimental data of jute fiber / polypropylene composites (data from Table 1).

Fig. 2A shows that when W_f is increased towards the transition W_f of 0.49, the porosity is relative small, and is only modestly increased. However, as W_f is increased above $W_{f\,trans}$, the porosity starts to increase dramatically. This is due to the situation where the fiber assembly is compacted to its minimum volume (i.e. V_f has reached $V_{f\,max}$), and the available matrix volume is insufficient to fill the free space between the fibers.

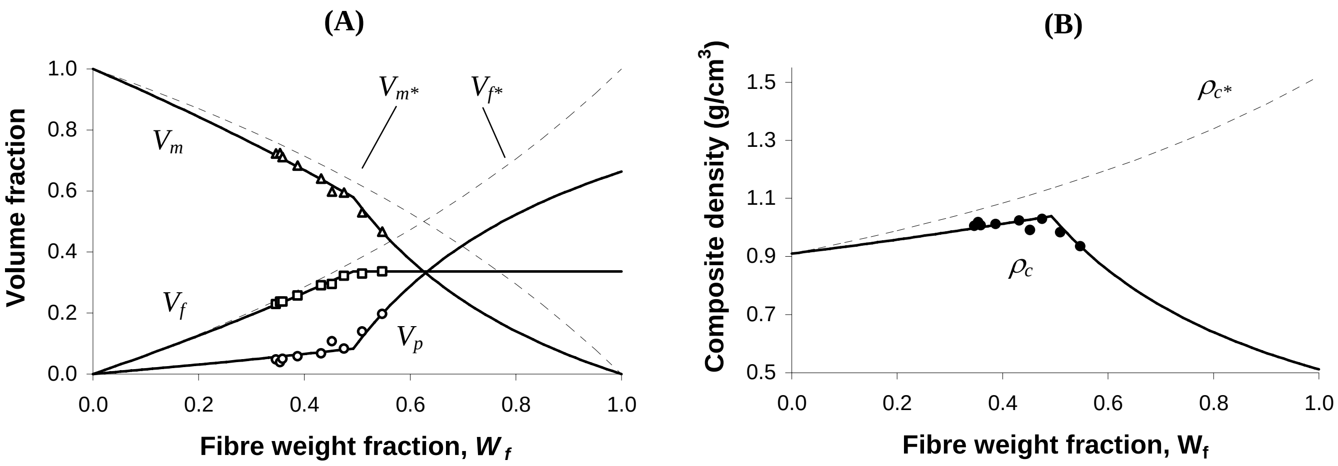

Fig. 2. Jute fiber/polypropylene composites: (**A**) volumetric composition and (**B**) density, as a function of the fiber weight fraction, W_f. Shown are experimental data of V_f (□), V_m (Δ), V_p (o) and ρ_c (•). Solid lines are model predictions of V_f, V_m ,V_p and ρ_c. Thin dotted lines are model predictions of V_{f^*}, V_{m^*} and ρ_{c^*} for composites with no porosity. The transition fiber weight fraction between the model cases A and B is 0.49.

Consequently, a large amount of porosity is formed, which is denoted structural porosity.

Fig. 2B shows that the density of the composites is increased towards a maximum value when W_f is increased towards $W_{f\,trans}$. When W_f is increased above $W_{f\,trans}$, the density is rapidly decreased due to the formation of structural porosity as seen in Fig. 2A.

In Fig. 2 at W_f equal to $W_{f\,trans}$, the fiber volume fraction is 0.34 (=$V_{f\,max}$), the porosity is 0.08, and the density is 1.04 g/cm^3. As can be seen in the figure, $W_{f\,trans}$ specifies a situation of an *optimal combination of high fiber volume fraction, low porosity and high composite density*.

The model predictions for composites with no porosity (Eqs. 1-3) are also shown in Fig. 2 to demonstrate that these deviate considerably from the experimental data, which necessitates that porosity is included in the calculations (Eqs. 4-11).

More examples of the good agreement between model predictions and experimental data of natural fiber composites are shown in the study by Madsen et al. [2].

4 Applications of model

The reliable predictions of composite volumetric composition and density make the model useful in design and process optimization of natural fiber composites.

4.1 Design of composites

In the perspective of composite fabrication, the model can be used to determine the fiber weight fraction needed to obtain a certain volumetric composition in the composites. As an example, if the jute fiber/polypropylene composites shown in Fig. 2 are made with a fiber weight fraction of 0.30, the model predicts that the composites will have a fiber volume fraction of 0.19, a matrix volume fraction of 0.76, and a porosity content of 0.05.

In general, weight fraction of fibers in composites need to be converted into volume fractions of fibers, matrix and porosity in order to estimate the expected mechanical performance of the composites (e.g. by micromechanical models).

As described above, when the criterion for good quality composites is the best obtainable combination of high fiber volume fraction and low porosity, the model allows prediction of the corresponding fiber weight fraction, which is equal to $W_{f\,trans}$.

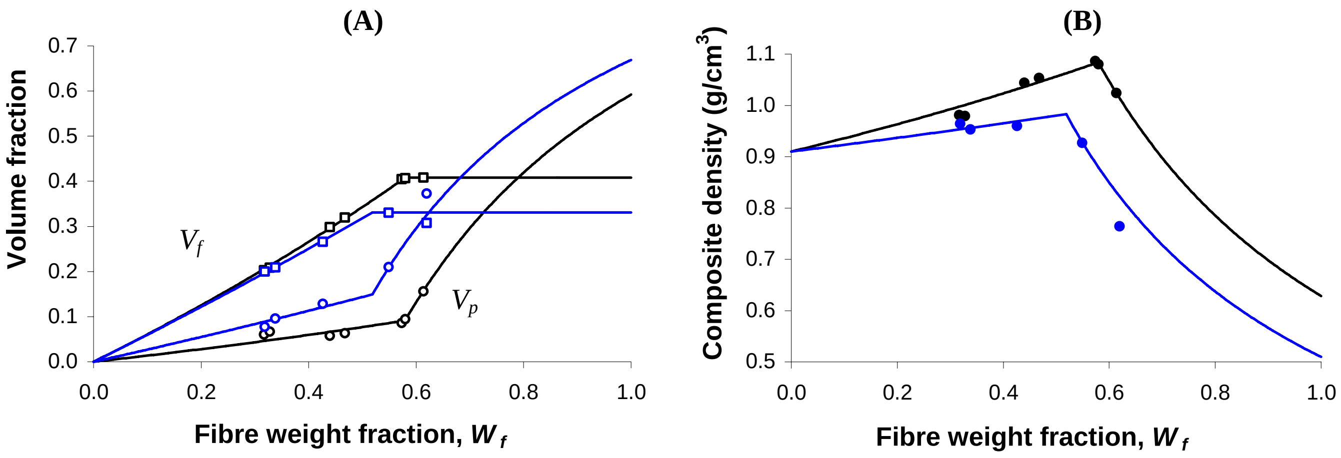

Fig. 3. Flax fiber/polypropylene composites: (**A**) volumetric composition and (**B**) density, as a function of the fiber weight fraction, W_f. Shown are experimental data of V_f (□), V_p (o) and ρ_c (•). Solid lines are model predictions. Shown results are from two identical composites with the same fibers and matrix, and fabricated by the same process, but consolidated by two different consolidation pressures of 0.7 MPa (blue) and 2.1 MPa (black). Exp. data are from a study by Toftegaard [4].

To make model predictions of the volumetric interaction in a given composite system requires a number of measurements. The density of fibres and matrix should be measured (e.g. by standard methods based on Archimedes principle). A minimum of 4 composite laminates with different fiber weight fractions should be fabricated, and their volumetric composition should be determined (e.g. by method described in a study by Madsen [3]). Based on these measurements, the model predictions can be fitted to the experimental data by adjustment of the three model parameters in Eqs. 4-11: $V_{f\ max}$, $\Sigma\alpha_{pf(i)}$ and $\Sigma\alpha_{pm(i)}$) (the latter two are porosity constants).

Finally, the model predictions can be used in the design of light weight composites; e.g. by selecting fibres with large luminal spaces. Low materials weight is a central selection criterion used for most industrial products (especially those that are made for transportation).

4.2 Process optimization of composites

The model can also be used to evaluate process optimization via changes in the volumetric interaction of the composites.

Fig. 3A shows the volumetric interaction in two natural fiber composites that are fabricated with a low and a high consolidation pressure of 0.7 and 2.1 MPa, respectively. Otherwise, the two composites are identical, i.e. the same fibers and matrix, and the same process conditions for time and temperature.

Fig. 3A illustrates very well the effect of an increased consolidation pressure on composite volumetric interaction; (i) the max. obtainable fiber volume fraction is increased from 0.33 to 0.41, (ii) the transition porosity is decreased from 0.15 to 0.09, and (iii) the transition fiber weight fraction is increased from 0.52 to 0.58.

Analogously, Fig. 3B shows that the max. obtainable density of the composites is increased from 0.98 to 1.08 g/cm^3 when the consolidation pressure is increased.

Thus, as demonstrated in Fig. 3, the model is well suited for a *quantitatively* based evaluation of any changes in composite process conditions (e.g. consolidation pressure, temperature, time or others). And as such, the model predictions of composite volumetric interaction can complement (or substitute) other commonly used approaches, such as mechanical testing which is more time-consuming and requires a larger amount of materials.

Acknowledgement

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