8. TENSILE STRENGTH

Models for the prediction of tensile strength are less well-developed and generally give poor predictions. [24, 27]

The particle-matrix bond is considered to act as an inherent flaw in the material when adhesion is poor. Poor adhesion basically precludes efficient stress transfer and the particle can therefore be seen as a void that weakens the composite. [24] A power law model may be used to describe the strength of a composite with poor adhesion. It assumes that the strength of the composite is determined by the effective available area of load bearing matrix due to the presence of the filler. [24]

$$\sigma_c = \sigma_p(1 - av_f^b) \tag{26}$$

Here a and b are constants that depend on the particle shape and orientation. These are the most important variables that determine the tensile strength of particular filled systems. [24] The tensile strength generally increases with a decrease in particle size as smaller particles provide a greater interfacial area. The result is a more effective interfacial bond. Particle size is also related to the flaw size dependence of the material, therefore the probability of finding a large flaw decreases with decreasing particle size. [24]

Irregular fillers are expected to weaken the composite owing to high stress concentrations around the sharp edges. A stress concentration factor can also be introduced to take into account the reduction in strength due to stress concentrations caused by irregular shapes.

$$\sigma_c = \sigma_p(1 - av_f^b)K \tag{27}$$

It is clear that the available models only predict an upper limit for the strength of the composite and that stress concentrations will lower these values by an undetermined amount. [24]

The model by Padawer and Beecher [27] for the Young's modulus was described earlier. They also postulated that the strength of the composite can be modelled in a likewise manner. If the maximum calculated stress in the particle is greater than the tensile strength of the particle, failure will be due to flake fracture. If the maximum calculated shear strength in the matrix exceeds the shear strength of the polymer, failure will be due to flake pull-out. It was found, however that the latter case is predominant in most cases. [27] The above situation, for the tensile strength in the plane of orientation, can be described by equation 28.

$$\sigma_c = v_p \sigma_p + K_3' \tau_p MPF \tag{28}$$

where

$$MPF = v_m \left(\frac{\alpha}{u}\right)\left(\frac{1}{\tanh(u)} - \frac{1}{u}\right)$$

$$u = \alpha \left(\frac{G_p v_f}{E_m (1 - v_f)}\right)^{\frac{1}{2}}$$

Apart from the deviations from ideal behaviour, which are accounted for by the factors K_3' (Equation 28) and K (Equation 27), both suffer the same limitation as do the models for Young's modulus. That is, the accuracy of predicting the tensile strength of the composite when the volume fraction polymer is approaching zero becomes very poor. Experimental data for tensile strength and stress at maximum load (in the plane of orientation) are presented in Figure 22, for LLDPE and phlogopite composites, as described in previous sections.

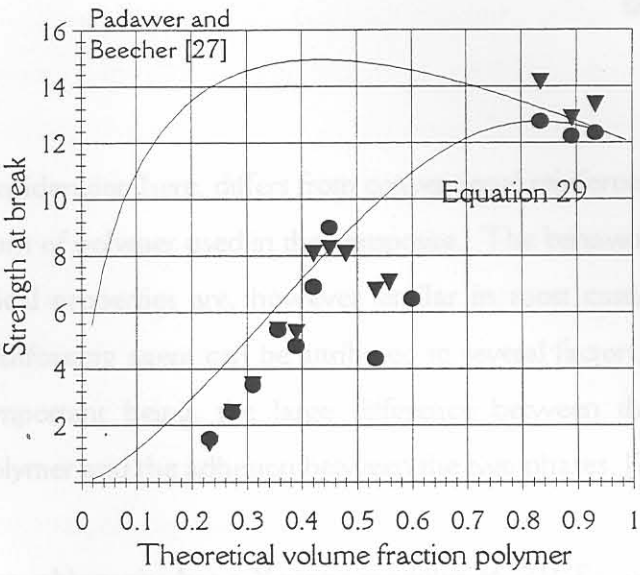

Figure 22: Maximum stress and stress at break. ■ Stress at break, 125 - 180µm, • Maximum stress, 125 - 180 µ, ▼, Maximum stress, 250 - 300 µm.

It is evident from the graph that equation 28 does not accurately describe the tensile strength of the composite at low volume fractions polymer. Accuracy can however be improved by realising that the voidage of the composite influences the effective available area of load bearing matrix. The matrix performance factor is therefore further reduced by the factor (1-χ), with χ defined as in section 6.4.2. The available area in the polymer phase is also reduced by the same amount. Equation 28 can therefore be modified to be:

$$\sigma_c = \left(v_p \sigma_p + K_3^{'} \tau_p MPF\right)(1 - \chi) \tag{29}$$

Figure 22 shows a comparison of Equation 29 with the present experimental data. A value for K_3' of 0.75 gives a reasonable fit. This modification resulted in a significant improvement in the correlation of the tensile strength and maximum stress, at low volume fraction polymer.

9. Discussion

The composite under consideration here, differs from conventional reinforced polymers mainly with respect to the amount of polymer used in the composite. The behavior of the composite with respect to mechanical properties are, however similar in most cases. Normally the reinforcing action of a reinforcing agent can be attributed to several factors, as pointed out in Chapter 3, the most important being, the large difference between the stiffness of the reinforcement and the polymer and the adhesion between the two phases. [7]

Considering the first point, phlogopite has a Young's modulus of 21GPa, while LLDPE has a Young's modulus of only 0.35GPa. One can therefore expect that the large difference between these values would cause a considerable stiffening effect in the polymer. The maximum stiffness that can be obtained is, however, not only dependant on the higher stiffness of the reinforcement. Several other factors also influence the stiffening effect of the reinforcement. These were pointed out in Chapter 3 as the size and shape of the reinforcement [12], the particle size [13] and distribution [14] and the concentration of the reinforcement. [13]

A somewhat surprising result is that of the effect of interfacial adhesion. The analysis of variance, as well as the initial scoping experiments (Chapter 6) revealed that the use of techniques normally effective in improving the adhesion of a non-polar polymer onto a polar mica surface was relatively unimportant compared to the other factors investigated. SEM micrographs also revealed that even with no modification to the polymer, good adhesion is obtained, evident from the thread-like edges around the particles after break (Figure 15).

From the results obtained in Chapter 6 in can be seen that in terms of the Young's modulus particle size and weight percentage polymer are indeed the most important parameters. The effect of polymer content was however slightly misleading due to non-linear effects not accounted for in the analysis of variance. Chapter 3 referred to the filler and mastic theory with regards to reinforced polymers [14]. The stiffening effect of the filler can therefore be accounted for not only by the packing efficiency, but also to the amount of polymer that is able to coat the particles. This coating around he particles effectively binds the particles together. If this coating is therefore discontinuous, or not adhere strongly to the surface, the results would be a material where the full potential reinforcing effect of the filler is not utilized. In the model for Young's modulus presented in Chapter 7, this effect was accounted for by modeling a voidage for the composite, which is dependant on the volume fraction polymer in the composite. In other words, if complete wet-out is not possible, because too little binder is present, the result would be the formation of voids, which will reduce the modulus of the composite.

Other effects that were not explicitly investigated was the particle size distribution of the reinforcement. In can, however, be expected that a distribution of particle sizes would result in an increase in the stiffening effect of the filler, as the smaller particles can increase the packing efficiency by packing in between the larger particles (filler theory). In the model for Young's modulus (Chapter 7) as well as the model for tensile strength (Chapter 8) the effect of particle size distribution would be accounted for in the maximum packing factor for that specific filler gradation.

In Figure 20 the concentration dependance of Young's modulus, predicted by the proposed model, compared with experimental results is shown. One important observation is the observed maximum value for modulus. This maximum shows that even with the large difference between the stiffness of the reinforcement and the binder, the maximum stiffness of the composites is considerably less than that of the filler. The maximum is strongly dependant on the aspect ratio of the reinforcement. It should therefore also be noted that as the aspect ratio is increased the model ultimately approaches the isostrain model, with the implication that the reinforcement is monolithic.

Other important aspects of this specific composite are the processing conditions that can greatly influence the modulus and tensile strength. Poor compaction of the filler and poor coating by the binder will result in excessive voidage, which will result in a lower than expected modulus and strength.

10. Conclusions

Phlogopite is brown mica that is produced as a mining by-product at Phalaborwa. Its availability and low cost make it a desirable filler and extender for polymer based composites. This study investigated the mechanical properties of compression moulded LLDPE / phlogopite sheets.

The Taguchi method was used to separately investigate the effects of composition and processing variables on the mechanical properties of compression moulded sheets. The composition variables considered were: particle size, polymer content and type of polymer modification. With respect to main effects (Young's Modulus) the factors particle size (32%) and polymer content (16%) were found to be the most important. However, these contributions to explaining the observed variance were small compared to the error term. The modulus showed a maximum value at a polymer content of approximately 20% by mass.

The processing variables considered were: holding pressure, mould temperature, moulding time and the amount of material moulded per unit area. Concerning the preparation variables, pressure contributed the most towards the Young's modulus (27%), although the contribution was small compared to the unexplained error. Pressure was a more important factor for the flexural modulus (70%). The highest tensile strength was obtained at the minimum value of 5 kg/m^2 material used.

For the present thermoplastic sheet composites it was not possible to achieve complete densification of the sheet material. The residual voidage was observed to depend on the amount of binder used. It also correlated with the maximum packing density of the pure reinforcement. The observed densities were intermediate to the theoretical upper and lower limits corresponding to complete wet-out and non-penetration of the filler bed.

A theoretical model for the Young's modulus, in the plane of reinforcement orientation, was derived. It is similar to the Cox [38], as modified by Padawer and Beecher [27] model. However, it also incorporates the effect of composite voidage on mechanical properties. Unlike other models, it correctly predicts the loss of modulus in the limit of zero binder. Good agreement was found between the predictions of this model and experimental measurements.

Compared to other models the new model predicts significantly lower values for the Young's modulus. At high volume fractions binder its predicted values are similar to those of the model by Padawer and Beecher [27]as well as the isostrain mixing rule.

A similar approach was used to correlate the composite tensile strength. Again a good agreement was found between the model and the experiment.