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Influence of a fine talc on the properties of composites with high density polyethylene and polyethylene/polystyrene blends

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Fine talc filled high density polyethylene (HDPE) and HDPE/polystyrene (PS) blends were extruded, injection moulded and characterized. Some of the mechanical properties of the talc filled HDPE and talc filled 75/25 HDPE/PS blend were deduced from stress–strain measurements. A comparison between the effect of the talc on the properties of the filled HDPE and filled 75/25 HDPE/PS blend showed that the mineral filler had the same effect on both systems provided that its array in the organic matrix is almost the same in both cases. In fact, the rheological results proved that the dispersion of talc in the HDPE matrix was not really affected by the presence of PS. The study particularly focused on the effect of talc on the ultimate tensile strength of the filled HDPE and that of the filled blend. It has been noted that the brittle nature of PS neutralizes, to a certain extent, the degrading effect of talc on this property. Furthermore, both PS and talc have a complementary effect on the stiffness and the resilience of HDPE/PS/talc blend composites.

1. Introduction

Particulate inorganic fillers are commonly added to commercial thermoplastic resins for reasons of economy and also to favourably modify properties such as stiffness, heat distortion, and mouldability. However, there is usually a trade-off involved with other important properties, such as toughness and ultimate elongation, which are usually degraded.

The minerals commonly used as fillers in plastic moulding compounds are calcium carbonate, alumina trihydrate, talc, mica, wollastonite, glass beads, silica, and clays.

Due to its lamellar nature, the use of talc generally leads to a reinforcing effect in polymers. Two of the main uses of talc are as a filler for polypropylene for use in vehicle applications and as a filler with anti-blocking properties in low and high density polyethylene [1, 2].

In semicrystalline polymers, talc can also initiate heterogeneous crystallization, thus changing the morphology of the matrix and conferring significant property changes [3]. In fact, the introduction of fine particles of talc provides a strong nucleating effect by multiplying the number of crystalline units in the material. Furthermore, the damaging effect of talc on the impact properties of a composite may be limited by using particles with a reduced size.

Concerning the poor properties of non-miscible polymer blends, fine talc particles were introduced in order to try to improve the tensile modulus and strength of the composite blend without a dramatic decrease in the ultimate properties.

To achieve this, we have investigated the influence of a fine talc by means of rheological, viscoelastic, morphological and mechanical characterizations on the properties of a 75/25 high density polyethylene (HDPE)/polystyrene (PS) blend. In order to do this, we decided to begin by studying the effect of talc on the performances of HDPE since it is the major polymer in the selected blend.

2. Experimental procedures

2.1. Materials

The polymers used in this study are Lacqtene 2003SN53 high density polyethylene (melt flow index (MFI) = 1.2 g per 10 min., 5 kg, 190 °C) and Lacqrene 1340 H polystyrene (MFI = 4 g per 10 min., 5 kg, 200 °C) both supplied by Atochem. Untreated talc, Steamic OOS commercial grade, was obtained from Talcs de Luzenac (median diameter: 2.39 μm, density: 2.78 g cm^{-3} and specific area: 10.9 $\text{m}^2\,\text{g}^{-1}$).

2.2. Processing

HDPE/talc and HDPE/PS/talc composite specimens were injection moulded (Sandretto Otto 95 T) from homogenized pellets extruded by a Clextral BC 21 twin screw extruder in which the filler is introduced in the melt zone. The extrusion conditions were a barrel temperature of 200 °C; a total weight rate of 6 kg h^{-1} and a screw speed of 350 r.p.m. The talc loadings were 5, 10, 20 and 30 vol % in HDPE and 20 and 28 vol % in the HDPE/PS blends. The talc content in the different composites was checked by ashing at 450 °C.

2.3. Morphological analysis

Analysis of the morphologies of the samples were carried out using a Jeol 35 CF scanning electron microscope (SEM) and an image analysis device. These analyses were performed on cryofractured surfaces of both injected and extruded samples. The image analysis provided quantitative information about blend morphology and the state of dispersion of the talc particles in the HDPE/talc composites.

2.4. Rheological characterization

The dynamic viscosity of melted pellets of the composites was measured by using the annular shearing method. The apparatus used in these studies was a viscoanalyser (Metravib Instruments) with a frequency range of 5–1000 Hz and a temperature range of 150–250 °C.

2.5. Thermal analysis

Differential scanning calorimetry (DSC) (Setaram DSC 92) was used to determine any nucleation effect of the talc in the composites. All the experiments were performed using the same temperature programme which was an increase of 3 °C min^{-1} up to 180 °C followed by a cool down at 2 °C min^{-1} repeated twice. The values of the temperature and crystallization enthalpy were recorded during the second cool down cycle. The mass of the sample ranged between 40–50 mg.

2.6. Mechanical characterization

Mechanical tests were performed on samples after a 48 h storage period at 23 °C and a 55% humidity. The elasticity modulus was determined at a deformation speed of 2.5 mm min^{-1} while tensile stress, yield stress and the corresponding deformations were obtained at a deformation speed of 25 mm min^{-1}. The apparatus employed in this experiment, an Adamel Lhomargy DY 26 machine, was fitted with an optical extensometer.

Impact resistance tests were carried out on notched Izod specimens according to the ISO 180 (1982) standard. All the mechanical tests were performed on at least ten specimens of each type of composite.

3. Results and discussion

3.1. HDPE/talc composites

3.1.1. Morphology

Micrographs of the HDPE/talc composites at different talc contents obtained by SEM on extruded samples are shown in Fig. 1 (a–d). It can be noted that the talc particles are randomly orientated in the HDPE matrix without a good adhesion as can be observed in Fig. 2.

Since the mechanical tests were carried out on injected samples, it will be interesting to investigate the effect of injection moulding on the state of dispersion of the talc particles in the HDPE. Obviously, injection moulding would have an effect on the break up of talc aggregates. Image analysis was carried out on several micrographs so as to determine the particle size distribution in injected and extruded samples with the same composition. The particle size distributions, represented here in terms of the surface area, that of extruded and injected samples are shown in Fig. 3. One can

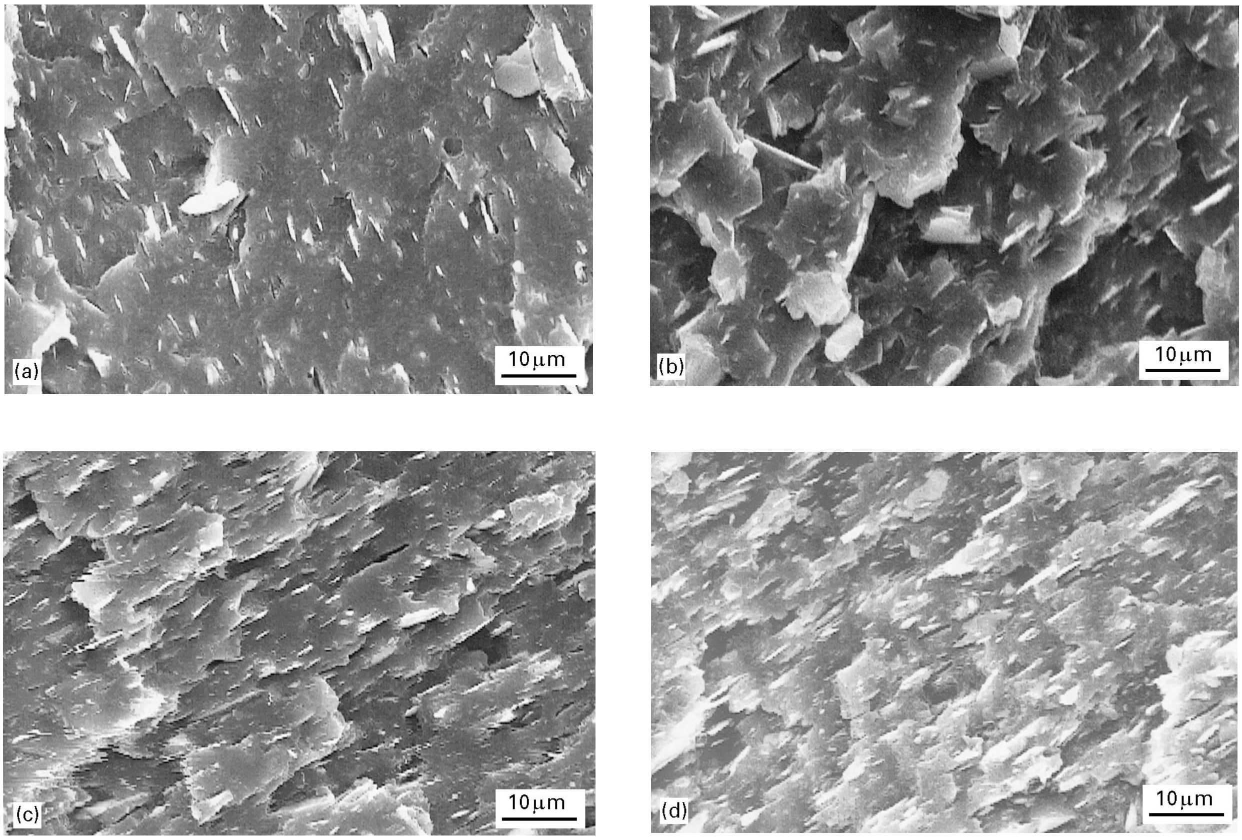

Figure 1 SEM micrographs of HDPE/talc extruded samples at talc contents of (a) 2 vol %, (b) 3.3 vol %, (c) 7.7 vol % and (d) 11.7 vol %.

Figure 2 SEM micrograph of a talc particle in the HDPE matrix.

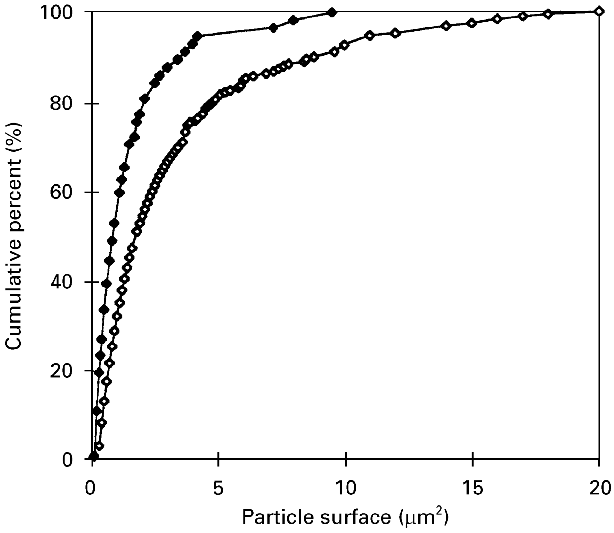

Figure 3 Talc particle surface distributions in; (◆) injected and (◇) extruded HDPE/talc samples.

observe that the surface area distribution curve for injection samples is lower than that for extrusion ones. It seems that the high levels of shear stress involved in the injection process causes a dramatic decrease in the talc particle size through deagglomeration.

3.1.2. Rheological behaviour

The dynamic viscosity of HDPE and its talc composites as a function of applied shear frequency for various filler volume fractions was determined. Talc based composites behave in a similar manner to pure matrix HDPE in that the viscosity increases with the talc content.

Many theories have been proposed to predict the rheological behaviour of rigid, spherical particle dispersions, the simplest being that of Einstein [4–6] which is illustrated by the relationship:

$$\eta_c/\eta_p = 1 + 2.5\phi \tag{1}$$

where η is the viscosity, the subscripts c and p representing the composite and polymer respectively whilst ϕ is the volume fraction of the filler.

This equation is valid only for low volume fractions (less than 0.1), and also for rigid, spherical particles that do not interact. For more concentrated dispersions, several equations have been proposed. Thomas [7] recommends an extension of Einstein's equation with identical assumptions:

$$\eta_c/\eta_p = 1 + 2.5\phi + 10.05\phi^2 + A\exp(B\phi) \tag{2}$$

where the parameters A and B equal respectively 0.00273 and 16.6.

Mooney [8] and Maron and Pierce [9] have taken into account the maximum packing fraction of the filler in the molten polymer (ϕ_m). According to Metzner [10], the equation of Maron and Pierce, carefully evaluated by Kitano *et al.* [11], seems to be the most appropriate to describe the effect of a filler on the rheological behaviours of a polymer:

$$\eta_c/\eta_p = (1 - (\phi/\phi_m))^{-2} \tag{3}$$

Experimental studies discussed by Metzner [10] proved that ϕ_m is dependent on the aspect ratio of the filler particles. For the unimodal distribution of several types of particles, different values of ϕ_m were proposed with a maximum value of 0.68 for spheres and a value of 0.44 for talc particles being attributed. Furthermore, it was noted that, for a given aspect ratio, ϕ_m increases where the particle distribution becomes multimodal. Nevertheless this effect is assumed to be low at particle contents less than 20 vol %.

Fig. 4 shows the experimental variations of the relative dynamic viscosity η_c/η_p as function of the talc content together with theoretical predictions using the models of Einstein, Thomas and also Maron and Pierce for various values of ϕ_m. It can be deduced from this figure that the calculated fit curves show only a poor agreement with the experimental data. Indeed even this level of fit was only achieved for a ϕ_m value of 0.68 using the Maron and Pierce equation. These differences may be attributed to: (i) interactions between talc particles, and (ii) a multimodal distribution of particles and aggregates.

According to Metzner [10], a matrix with a pronounced viscous character may prevent interactions between filler particles since the viscous forces would

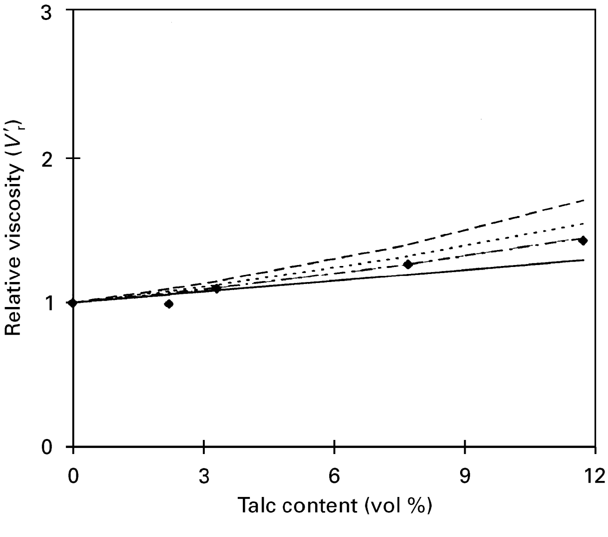

Figure 4 Variation of the relative dynamic viscosity η_c/η_p at 7.8 Hz for HDPE as a function of talc concentration. Key: (◆) experimental points, (—) fit to Einstein model, (–•–) fit to Thomas, (– – – –) fit to Equation 3, $\phi_m = 0.5$, (. . .) fit to Equation 3, $\phi_m = 0.6$ and (–•–••) $\phi_m = 0.7$.

tend to limit aggregation processes. While the HDPE used in this study has a high viscosity, the talc present in the different composites still exists in the form of aggregates. This may be due to the fact that talc aggregation occurs before incorporation and that the stresses involved in extrusion are unable to break up the aggregates efficiently.

3.1.3. Thermal analysis

According to Pukanszky *et al.* [12] and Rybnikar [13], mineral fillers may strongly modify the crystallization process of semicrystalline polymers in a quantitative and qualitative manner. These modifications concern mainly: (i) the size and orientation of the crystalline units (spherolites, lamellae), (ii) the crystalline fraction, and (iii) the crystallization peak temperature.

It has been shown by Wunderlich [14] that in unfilled commercial polyolefins, nucleation is mainly heterogeneous. The nucleating effect is usually attributed to catalyst residues. However, the nature of the nucleation sites is not always well known. Metastable and stable nucleation centres have been observed by Rybnikar [13] in polypropylene. In talc filled polypropylene, Rybnikar observed that the number of nucleation centres is greater than in unfilled polypropylene. This leads to the growth of a large number of smaller crystalline units.

In the case of isothermal crystallization, Rybnikar has shown that above 5–10 vol % talc contents in polypropylene, there is no further increase in the crystallization rate. This suggests to the current author that only a fraction of the talc particles' surface seems to play a role in nucleation. Moreover, the nucleation activity probably involves some crystalline faces of the filler or sites such as pores and cracks [15]. For example, polypropylene chains are found to align themselves regularly on the basal planes of talc sheet particles; however this tendency is less marked in the case of polyethylene [3].

The nucleating effect of a talc will thus depend on its geomorphological and geochemical nature as well as the ore processing treatments (grinding, micronization, etc) necessary to obtain a given size distribution.

DSC analyses were performed on the different composites in order to evaluate to what extent the talc may influence the crystallization kinetics of the HDPE. The results are presented in Fig. 5. One can note a broadening of the crystallization peaks as the filler fraction increases. This phenomenon may be ascribed to different heterogeneous nucleation mechanisms. Table 1 indicates the evolution of the crystallization peak and the variation in crystallization enthalpy.

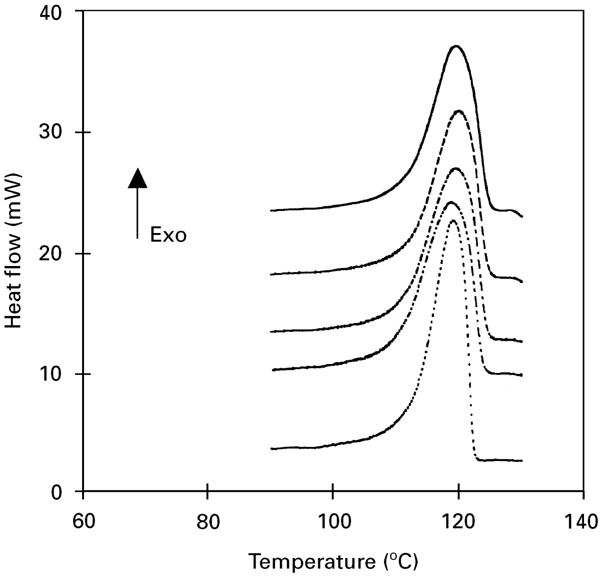

Figure 5 DSC thermograms (crystallization) of HDPE and its composites with talc. The cooling rate is 2 °C min^{-1}. Talc contents of: (···) 0 vol %, (– · · –) 2 vol %, (· – · – ·) 3.3 vol %, (– – –) 7.7 vol % and (——) 11.7 vol %.

The crystalline fraction seems to increase continuously with the talc level, however, the kinetics appear to be unchanged beyond a loading of 9 vol %. This latter tendency agrees with the results of Rybnikar [14] for talc–polypropylene composites. Hence, it can be deduced that there is a limit to the possible reduction in the crystalline unit size achievable by using high concentrations of inorganic crystallinity promoters such as talc.

3.1.4. Mechanical characterization

On the whole, lamellar mineral fillers reinforce polymers thus improving rigidity. The variation of the tensile modulus of HDPE as a function of talc content is shown in Fig. 6 along with points corresponding to the theoretical models usually used for analysis of data obtained from filled polymers. These models assume spherical particles, a perfect adhesion between filler and polymer and a perfect dispersion in the matrix. Einstein's equation is one of the simplest [4], which is derived from the analogous viscosity relation:

$$E_c = E_m(1 + 2.5\phi) \tag{4}$$

TABLE I Crystallization properties of HDPE/talc and HDPE/PS/talc composites

	HDPE					75 HDPE/25PS		
Talc fraction (wt %) (vol %)	0 0	6 2	9 3.3	20 7.7	28 11.7	0 0	20 7.7	28 11.7
Crystallization temperature peak (°C)	117.7	118.7	119.6	120.1	119.5	116.6	119.3	119.8
Heat of crystallization (J g^{-1} of PEHD)	209.4	217.1	220.3	228.0	236.4	167.2	215.6	234.1

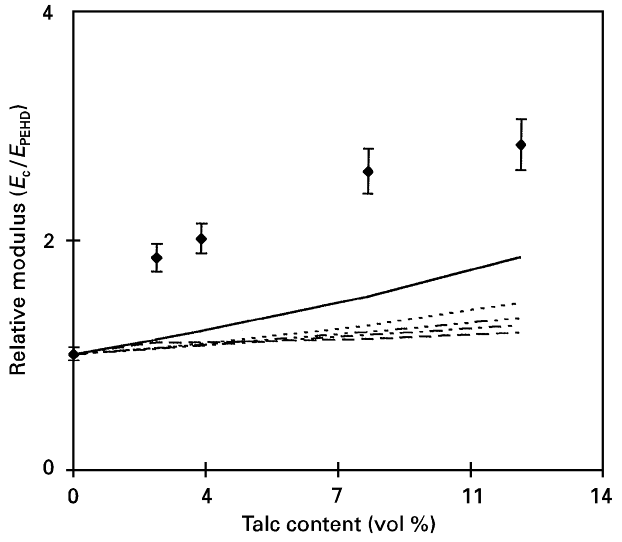

Figure 6 Tensile modulus versus talc volume fraction for HDPE/talc composites. Key: (◆) experimental points, (–·–··) fit to Einstein model, (perfect adhesion), (–––·) fit to Sato and Furukawa (perfect adhesion), (——) fit to Nielsen (0.42), (– ·–·) fit to Nielsen (0.68), (···) fit to Guth and Smallwood.

where E_c is the composite modulus, E_m is the matrix modulus and ϕ is the filler content.

Guth [17] and Smallwood [18] have modified Einstein's equation to take into account the existence of interparticle interactions:

$$E_c = E_m(1 + 2.5\phi + 14.2\phi^2) \tag{5}$$

Sato and Furukawa [19] have developed an expression in which the matrix can deform with the resultant formation of elliptic cavities around each inclusion:

$$E_c = E_m\left\{\left(1 + \frac{1}{2}\frac{y^2}{1-y}\right)\left[1 - \frac{y^3\tau}{3}\left(\frac{1+y-y^2}{1-y+y^2}\right)\right] - \frac{y^2\tau}{3(1-y)}\left(\frac{1+y-y^2}{1-y+y^2}\right)\right\} \tag{6}$$

where $y = \phi^{1/3}$.

Two limiting cases correspond to the extreme values for the parameter τ: namely (i) $\tau = 0$ (perfect adhesion) and $\tau = 1$ (no adhesion and cavity formation). Other expressions have also taken into account the aspect ratio of the filler particles. Halpin [20] and Tsaï [21] have suggested the following equation:

$$\frac{E_c}{E_m} = \frac{1 + AB\phi_d}{1 - B\phi_d} \tag{7}$$

where $B = (E_d/E_m - 1)/(E_d/E_m + A)$, E_d is the modulus of the dispersed phase and $A = 2(l/d)$ with l/d representing the aspect ratio.

Lewis and Nielsen [22] have proposed another form of the previous equation which considers the maximum packing fraction of the filler ϕ_{max}:

$$\frac{E_b}{E_m} = \frac{1 + AB\phi_d}{1 - B\psi\phi_d} \tag{8}$$

where

$$\psi = 1 + \left(\frac{1 - \phi_{max}}{\phi_{max}^2}\right)\phi_d$$

All these equations assume a perfect adhesion between the polymer and filler and a perfect dispersion of the particles.

Although the modulus appears to be independent of the filler particle size, experimental studies reported by Nielsen [23] have shown that the modulus of a composite may vary with particle size. Moreover, the size distribution has an influence on the ϕ_{max} parameter, since a broad distribution gives a better packing (a high ϕ_{max}). According to Lewis and Nielsen's equation, a high compactness reduces the modulus. The particle shape also plays a significant role. In fact, Nielsen [28] and Wu [25] have independently pointed out an important increase in the modulus caused by an effective orientation of the lamellar particles. Moreover, fillers with a nucleating effect could improve the stiffness by enlarging the crystalline fraction in semicrystalline polymers.

The experimental results and plots of the theoretical predictions are presented in Fig. 6. Two values are proposed for the maximum packing fraction in the model of Nielsen: 0.42 and 0.68. The former corresponds to an aspect ratio of 10, close to that of the talc used, the latter, corresponds to an aspect ratio of 2, which represents the case of a random packing of identical spheres [26]. The experimental data are compared to theoretical plots calculated using Equations 4–8. One can note that all the theoretical curves fall far below the experimental one. This may be explained by the following reasons: (i) most of the models assume identical spherical particles, (ii) the filler to matrix modulus is assumed to be close to 10, this assumption is not valid in the case of talc/HDPE composites, (iii) disaggregation phenomena caused by the processing operations may influence the maximum packing value in the Nielsen model, and consequently the modulus, (iv) a perfect dispersion of the filler is assumed, however the presence of filler agglomerates and aggregates may lead the actual volume fraction of the filler in the composite to be higher, causing the modulus to be underestimated, and (v) particle orientation is not taken into account in the various models. However, Nielsen [24] has mentioned that orientation strongly influences the Young's modulus.

A sharp alignment of particles is observed in this work by SEM, and enhanced crystallization caused by the presence of talc is not taken into account, although the influence of the amount of crystallized fraction in the polymers on their modulus is well-known.

Compared to the numerous well-developed models for predicting the modulus of polymer composites, models for predicting their tensile strength are relatively few and poorly developed. Generally, there is a reduction in the tensile strength as a function of filler loading.

Sahu and Broutman [27] considered that the presence of stress concentration around filler particles causes a decrease in the tensile stress. In addition, Nielsen (28) has noted that a decrease in this property in filled polymers depends on the reduction of polymer fraction in the transverse cross-section of a specimen. Nicolais and Nicodemo [29] have proposed an expression for the tensile stress as a function of filler fraction:

$$\sigma_c = \sigma_m(1 - a\phi^b) \qquad (9)$$

where a and b are constants that depend on the stress concentration and filler geometry respectively. In the case of spherical fillers which do not adhere to the matrix, a has a value of 1.21. Conversely, if the filler does adhere to the matrix, less stress is induced by the filler and the parameter a is equal to 1. The value of b is determined by the fracture mode. In the case of random fracture which probably propagates throughout the matrix, b equals 1, whereas in the case of a fracture which goes through the filler–matrix interface, b equals 2/3. Consequently, there is an upper and a lower limit to the tensile strength. The former case corresponds to the pair of values ($a = 1$, $b = 1$) while the latter corresponds to the pair ($a = 1.21$, $b = 2/3$).

A comparison between the experimental data and the two theoretical limits is presented in Fig. 7. The experimental data fit the lower limit rather well. This may be attributed, to either lack of adhesion at the filler–matrix interface or to the existence of strong stress concentrations at this interface due to the lamellar character of the talc (see Fig. 2).

The formation of cavities is believed to be related to the extent of deformation involved; the more deformation there is, the more cavities there are. Fig. 8 shows the evolution of the deformation at break as a function of talc fraction. One can observe an increase in this property up to a fraction of 4 vol %, followed by a decay for higher values of talc content.

Generally, the incorporation of mineral fillers in thermoplastic polymers entails a decrease in the ultimate strain rate. However, Nicolais and Nicodema [29] and Lavengood *et al.* [30] noted that the presence of cavities around filler particles could outweigh this phenomenon. They suggested that if the propagating crack encounters a filler particle to which the matrix is not strongly adherent, then interfacial debonding can effectively blunt the tip of the crack and prevent or, at least slow down, further propagation of the cracks.

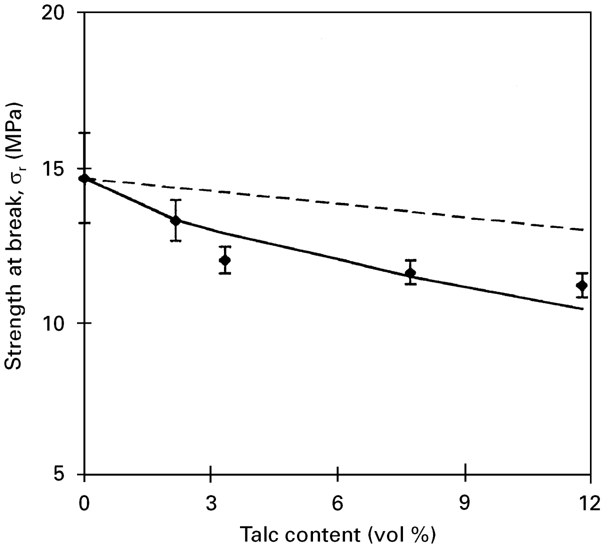

Figure 7 Comparison between the experimental data of ultimate tensile strength for HDPE/talc composites and the two theoretical limits given by Equation 9. Key: (◆) experimental points; (– – –) $a = 1$, $b = 1$; (——) $a = 1.21$, $b = 2/3$.

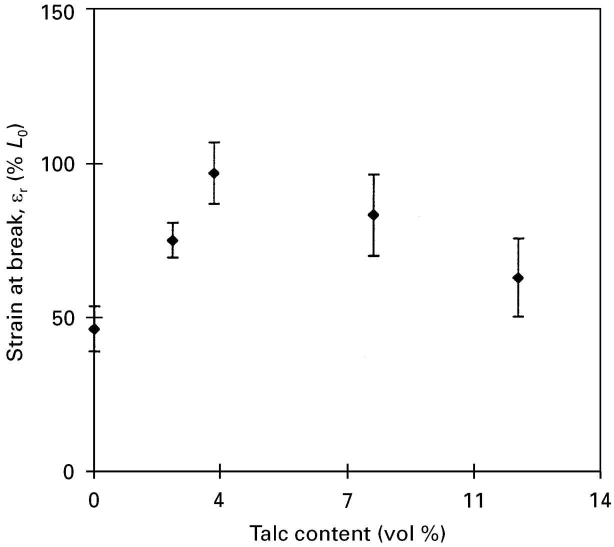

Figure 8 Evolution of deformation at break of HDPE/talc composites as a function of talc content.

The study also focussed on impact resistance behaviour. As in the case of ultimate strain, a decrease in impact resistance is generally forecast in filled polymers. An exception may involve ultrafine quasi-spherical fillers [31]. According to Bigg [32] all attempts to model the impact resistance of filled polymers are unsatisfactory.

Fig. 9 presents the evolution of notched Izod impact resistance as function of talc fraction. A steady decrease can be noticed. It is thought that the ductile

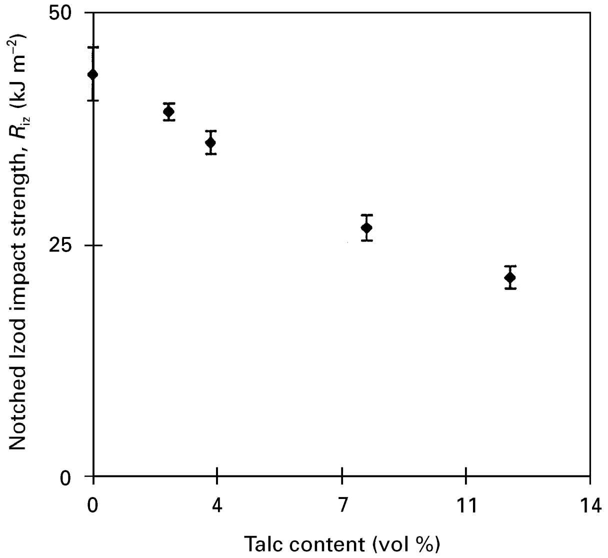

Figure 9 Notched Izod impact strength versus talc content for HDPE/talc composites.

character of HDPE and the fineness of the talc somehow limited the degradation in the impact strength.

3.2. HDPE/PS/talc composites

In this part, the effect of the talc filler on the overall performance of a 75/25 HDPE/PS blend was examined in light of the above examination of its effect on pure HDPE. The objective is first to evaluate the effect of talc on the properties of HDPE in the presence of polystyrene, secondly, to study the effect of a mineral filler on the properties of an incompatible blend.

3.2.1. Morphological analysis

The effect of talc on the microstructure of the 75/25 HDPE/PS blend corresponding to an extruded sample is shown in Fig. 10. It can be observed that the dispersion-like morphology of the HDPE/PS blend, usually observed in such blends [33, 34], is not affected by the presence of the mineral filler. The latter is mainly dispersed in the HDPE matrix.

3.2.2. Rheological characterization

The variation of the dynamic viscosity of the filled blend ($\phi = 7.9\%$) as a function of frequency is shown in Fig. 11. Plots corresponding to the Kitano [11] equation with different values of ϕ_m are represented (see Equation 3). There is a rather good agreement between the experimental plot and the theoretical one for a ϕ_m value of 0.7, bearing in mind that this was also the case for filled polyethylene.

It can be concluded from this result that the talc particles are identically arrayed in the filled blend and the filled HDPE. As mentioned in section 3.1.2, the highly viscous character of the matrix should prevent interactions between filler particles. The introduction of PS, with a lower viscosity than HDPE, in the system has no significant effect on the viscosity level and therefore little effect on the array of talc particles.

3.2.3. Thermal analysis

The results of thermal analyses on the filled HDPE/PS blends are summarized in Table 1. It can be noted that the talc has a similar effect on the crystallization of pure HDPE to that of the blend. In fact, the crystallization peak temperatures of the filled blends are very close to those of filled HDPE. The nucleating effect of talc, observed for blend crystallization may be considered the same as that observed for HDPE.

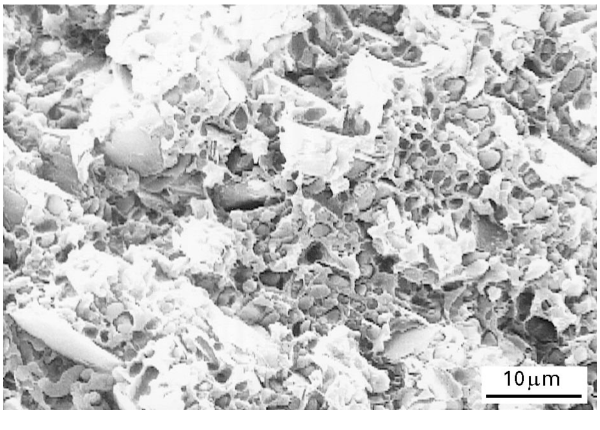

Figure 10 SEM micrograph of a 75/25 HDPE/PS blend filled with 7.9 vol % of talc.

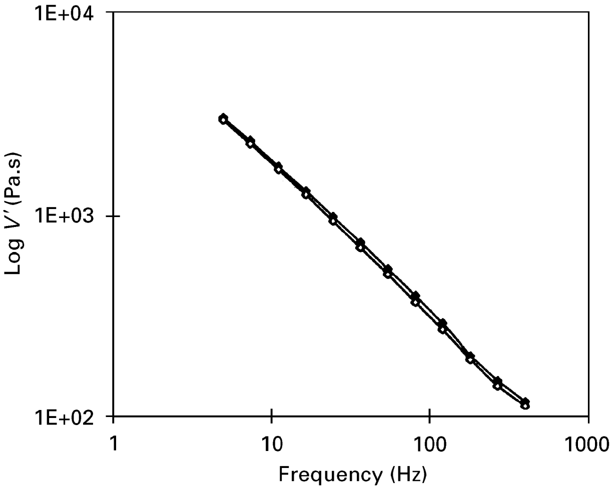

Figure 11 Variation of dynamic viscosity of talc filled 75/25 HDPE/PS blend (talc content = 7.9 vol %) with plot corresponding to Equation 3 with $\phi_m = 0.7$. Key: (◆) experimental points, (◇) theoretical points.

3.2.4. Mechanical characterization

Concerning the mechanical properties of filled 75/25 HDPE/PS and considering the results of the rheological analysis, the above system will be assumed to be a classical filled thermoplastic composite in which the 75/25 HDPE/PS blend plays the role of a matrix. The experimental results will be compared with plots of the same theoretical approaches as in the case of talc filled HDPE.

First, in the case of the modulus, the experimental data are only compared with the Nielsen model (see Equation 9) with a ϕ_{max} value of 0.42. This model seems to be the best one to describe the effect of talc on the modulus as was shown above (see Section 3.1.4). The value of the matrix modulus in this model will be replaced by that of the blend.

The variation of the blend's Young's modulus as a function of the filler content compared to a plot corresponding to the Nielsen model is presented in Fig. 12a. It shows that there is a good agreement between the experimental results and the theoretical plot. The small observed deviation may be explained using the same reasons mentioned previously (see Section 3.1.4.). In addition, talc and PS seem to work in a complementary way on the HDPE modulus in that both contribute to the reinforcement of HDPE. Fig. 12b shows the effect of PS content on the tensile modulus of HDPE. The blends were produced using the same conditions as those for the composites.

In contrast to the effect on the modulus, talc and PS act in opposite manners on the tensile strength of HDPE based composites and blends. Schwarz *et al.* [35] have reported that PS enhances the tensile

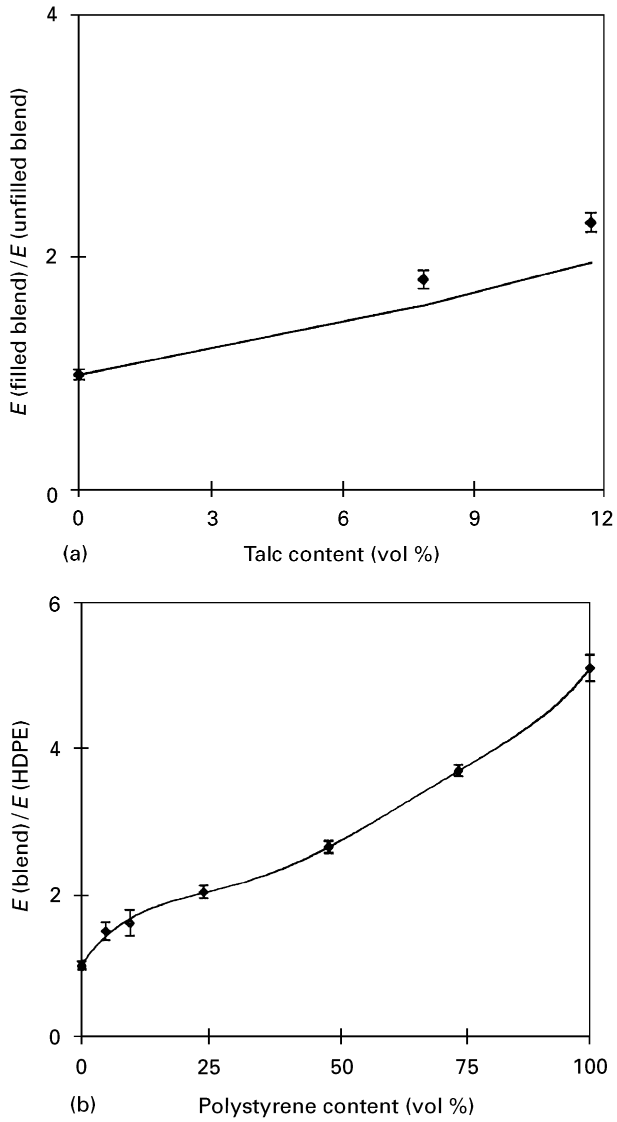

Figure 12 (a) Variation of relative tensile modulus of the 75/25 HDPE/PS blend as a function of talc content compared to the theoretical plot corresponding to Equation 8 ($\phi_m = 0.42$). Key: (◆) experimental points, (——) theoretical fit, and (b) the variation of tensile modulus HDPE as function of PS.

strength of HDPE/PS blends, however, we observed that the talc reduces this property (see Section 3.1.4). This reduction is related to cavity formation around talc particles.

It was previously noted that the equation of Nicolais and Nicodemo [29] with $a = 1.21$ and $b = 2/3$ fitted the experimental results rather well for the talc/HDPE composites. Consequently, an equation derived from the above one [9] could be applied to talc filled HDPE/PS blends. This equation may be written in the form:

$$\sigma_c = \sigma_b(1 - 1.21\phi^{2/3}) \qquad (10)$$

where b and c represent the blend and the composite respectively.

The evolution of the tensile strength as a function of talc content and a comparison plot corresponding to Equation 10 are shown in Fig. 13. The experimental data show a slight increase in tensile strength whereas the equation predicts the opposite trend. We noted in Section 3.1.4 that the decrease in tensile strength is related to cavity formation and that moreover this phenomenon is believed to be as important as the strain involved.

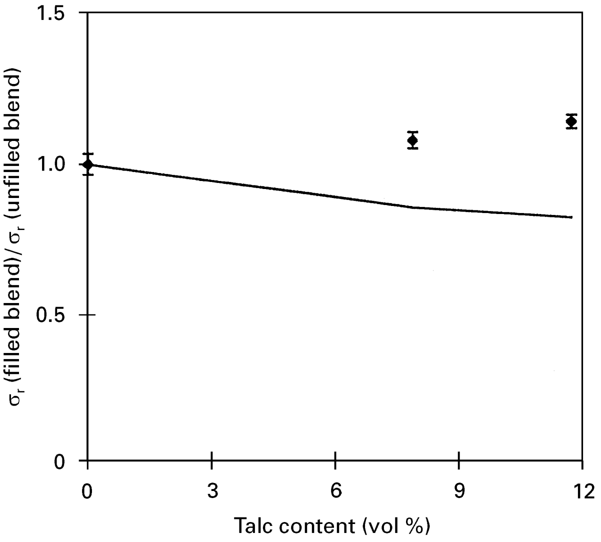

Figure 13 Variation of relative tensile strength at break of the 75/25 HDPE/PS blend as a function of talc content with a theoretical plot corresponding to Equation 10. Key: (◆) experimental points, (——) theoretical plots.

Schwarz *et al.* [35] have reported that blending PS with HDPE in the proportions 25 to 75 vol % leads to a brittle material. In consequence, the ultimate strain is reduced, and so is the cavity formation. Fig. 14 shows the evolution of deformation at break of the 75/25 HDPE/PS blend as function of talc concentration. Because of the brittle nature of the blends, the level of deformation is lower than that noticed in the talc/HDPE composites (see Fig. 8). Therefore, the negative effect of talc on the tensile strength is cancelled out and one can suppose that at such low levels of deformation, talc acts as a reinforcing agent on the blend.

We were also interested in the effect of talc on the impact resistance of the blend composite. Fig. 15

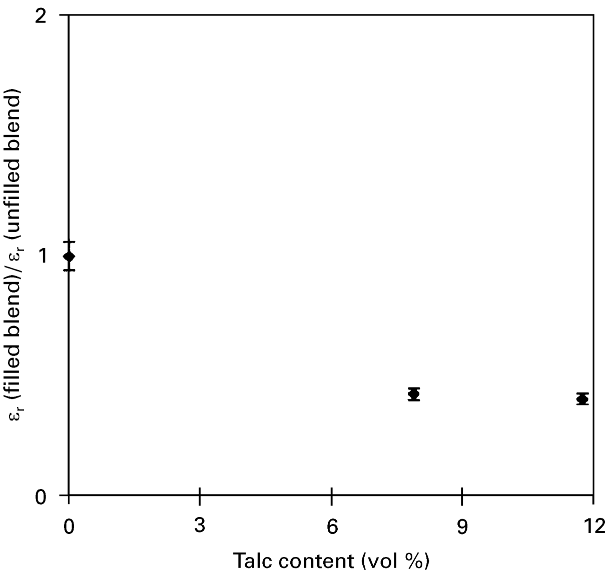

Figure 14 Evolution of deformation at break of the 75/25 HDPE/PS blend as a function of talc content.

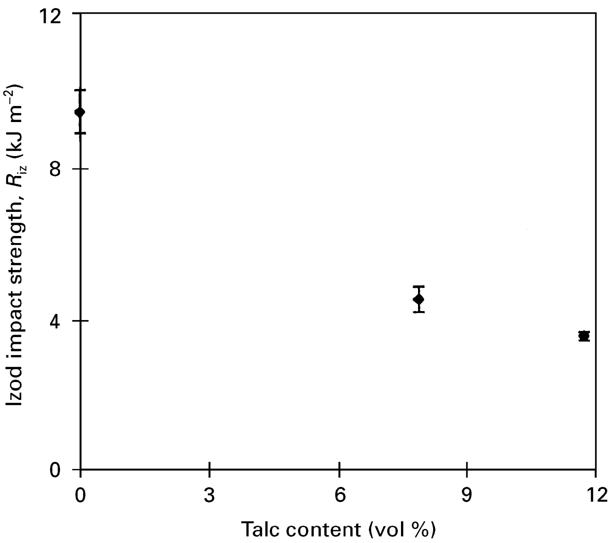

Figure 15 Variation of the notched Izod impact strength of the 75/25 HDPE/PS blend as a function of the talc content.

shows the evolution of the notched Izod impact resistance of the 75/25 HDPE/PS blend as a function of talc content. One can observe a steady decrease in resilience for the filled blend with increasing talc content which seems to be more significant in the filled blend than in the filled HDPE. This difference may be ascribed to the brittle nature of the blend. These results underline that both PS and talc act in the same way on the impact strength and their effects appear to be complementary. Even though no affinity between PS and talc is observed in the blend composite (see Fig. 10), fracture paths and mechanisms probably involve both of these minor phases.

4. Conclusions

The effect of fine steamic talc on the overall performances of HDPE and a 75/25 HDPE/PS blend were investigated. Thermal analysis highlighted the nucleating effect of talc on HDPE, furthermore rheological measurements emphasized the effect of the talc particle array (fraction of maximum packing) on the flow behaviour of filled HDPE. It was noted that talc has an appreciable nucleating effect on the crystallization of HDPE. This effect was not significantly affected by the presence of PS. In fact an increase in the heat of crystallization with talc was observed for HDPE and the 75/25 HDPE/PS blend.

As far as mechanical properties are concerned, it was observed that different factors make the prediction of the elastic modulus by means of theoretical models somewhat difficult. Nevertheless, it appeared that Nielsen's model seems to be the most appropriate.

The lack of adhesion between the matrix and filler with the presence of strong stress concentrations around particles lead to a substantial decrease in the ultimate strength. The formation of cavities around talc particles during the tests resulted in an increase in the ultimate strain.

The effect of talc on the properties of the 75/25 HDPE/PS blend was evaluated in relation to its effect on those of HDPE. The results obtained showed that the effect of talc on both mechanical and rheological properties is similar for both HDPE and its blend with PS.

In addition, it was noted that the ultimate tensile strength of the filled blend seems to be determined by the positive contribution of PS. The effect of talc is neutralized by the brittle nature of PS which leads to a small amount of cavity formation around the talc particles. Furthermore, talc and PS seemed to have a complementary effect on the other properties.

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