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Research article

Comparison of the effect and efficiency of two impact modification approaches in polypropylene

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Abstract. Polypropylene (PP) hybrid composites were prepared with talc, a reinforcing filler, and an additional impact modifier. Impact resistance was improved by the use of a traditional elastomer and by the new approach of adding a synthetic polymer fiber, poly(vinyl alcohol) (PVA), in this case. The results showed that the use of PVA is more efficient than that of the elastomer. The latter decreases stiffness considerably, from the 3.5 GPa value of the PP/talc composite to around 1.5 GPa, it does not carry practically any load, and even its impact modification efficiency is somewhat smaller than that of the PVA fibers. On the other hand, PVA increases stiffness to some extent, up to 5 GPa, tensile strength considerably, especially in the presence of a coupling agent, and the large impact resistance of 20 kJ/m^2 can be achieved with it at moderate fiber contents. The positive property profile achieved is the result of the local deformation mechanisms occurring in the PP/talc/PVA composites. Properties can be further adjusted to purpose by the application of a functionalized PP coupling agent.

Keywords: *polymer composites, mechanical properties, modeling and simulation, industrial applications*

1. Introduction

Polypropylene (PP) is one of the commodity polymers used in the largest quantity in all fields of applications. Its growth rate is very large due to its excellent price/performance ratio and its rather low carbon footprint [1, 2]. PP is one of the preferred polymers in the automotive industry for several reasons [3–5]. The stiffness of PP homopolymers is usually around 1.5 GPa, which can be increased to 1.7–2.0 GPa by the appropriate selection of polymerization technology and nucleation [6, 7]. Its strength is also acceptable at around 30 MPa. Moreover, the price of PP is affordable, and recycling is easy. This polymer has the additional advantage that it can be modified in a number of ways to adjust its property profile to the intended application [8–16].

One of the weaknesses of PP homopolymers is their relatively small room temperature impact resistance, which is around 2 kJ/m^2 for typical injection molding grades. However, in structural applications, very often, larger impact resistances are required. The automotive industry, for example, prefers impact resistances at around 15–20 kJ/m^2, which requires the impact modification of the polymer. The traditional way

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to improve the impact resistance of PP is its blending with an elastomer, preferably an ethylene-propylene (EPR) or ethylene-propylene-diene (EPDM) copolymer [17–24]. Unfortunately, this traditional approach of adding an elastomer to PP has the disadvantage that the stiffness of the resulting blend decreases as the amount of the impact modifier increases in the blend [14–16]. However, large stiffness and impact resistance is frequently required, which cannot be achieved in this way. The targeted property profile in the automotive industry, for example, is the combination of stiffness and impact resistance larger than 2 GPa and 15 kJ/m^2, respectively. In order to achieve this combination of properties, hybrid composites are prepared containing an elastomer impact modifier and a filler or fiber to increase stiffness. Good results have been achieved with this approach, and several PP grades are available on the market using this principle [15, 25–28].

The combination of an elastomer and a filler or fiber frequently leads to further complications. Various structures can be formed in such compounds since the elastomer can partially or completely embed the filler. Accordingly, two boundary structures can form depending on interfacial interactions and processing conditions [29]: the separate dispersion of the components in the PP matrix [30, 31] or the complete embedding of the filler by the elastomer, and the dispersion of these composite particles in PP [25, 26, 32]. As previous results show, the separate dispersion of the two components is more advantageous and facilitates the achievement of the property combination mentioned above [25, 26, 29–31]. Although the approach of using an elastomer and a filler proved to be quite efficient in many cases, the approach failed completely in composites reinforced with natural fibers in which impact resistance remained very small even at relatively large elastomer contents [33, 34].

Recently, a new approach of using synthetic polymer fibers for impact modification has been proposed to overcome the problem [35–44]. The addition of these fibers increased impact resistance considerably in injection molded PP parts but did not decrease, occasionally even increased stiffness [35–40]. The approach has been successfully used in PP composites containing traditional reinforcements, like glass or carbon fibers [41–43], but also in materials prepared with natural reinforcements like flax, sugarcane bagasse, or sugar palm fibers [44]. Although the two approaches have been known for some time, their benefits and drawbacks have never been compared and analyzed, at least according to the best of our knowledge.

Accordingly, the goal of this study was to remedy the situation and compare the impact modification effect and efficiency of an elastomer and a synthetic polymer fiber in polypropylene hybrid composites in order to find the best solution for industrial practice. Talc has been chosen as the reinforcing filler to increase stiffness since it is a cheap but very efficient reinforcement often used in PP because of the additional benefit of strong nucleation resulting in homogeneous structure and advantageous properties. An octene-1 elastomer and poly(vinyl-alcohol) (PVA) fibers were chosen as impact modifiers, and their effect was compared to each other. PVA fibers were selected for the study since previous results [45] proved that their larger load-bearing capacity offers a better combination of properties than the use of the more common and relatively cheap polyethylene terephthalate (PET) fibers. The attention was focused on stiffness and impact resistance, but the structure of the composites, as well as the reinforcing effect of the two additives, were also analyzed together with structure-property correlations. The property profile mentioned above, *i.e.*, 2 GPa stiffness and 15 kJ/m^2 impact resistance, was always kept in mind during the analysis of the results, and the practical relevance of these latter is also considered at the end of the paper.

2. Experimental

2.1. Materials

The polypropylene used in the experiments as a matrix was the Daplen HJ 325 MO grade homopolymer produced by Borealis GmbH, Linz, Austria. The polymer has a melt flow rate (MFR) of 50 g/10 min at 230 °C, 2.16 kg, and a density of 0.91 g/cm^3. The reinforcing filler was the Jetfine 3CA talc obtained from Imerys Performance Minerals (Paris, France). The average particle size of the filler is 6.0 μm, and its aspect ratio is 10. The filler has a specific surface area of 13.3 m^2/g, its density is 2.78 g/cm^3, and the dispersive component of its surface energy measured at 100 °C is 172 mJ/m^2.

The effect of two impact modifiers was compared in the project. The elastomer representing the traditional solution was the Queo 7001 LA ethylene-octene-1 copolymer with an MFR of 10 g/10 min at 190 °C and 2.16 kg and a density of 0.87 g/cm^3. The elastomer

was produced by Borealis GmbH. The other impact modifier was the Kuralon VPB 103 PVA fiber obtained from Kuraray Co., Ltd., Tokyo, Japan. The initial length of the fibers was 3 mm, and their diameter was 11 μm. The modulus of the fibers is 10 GPa, while their tensile strength is 780 MPa, according to the producer. The density of the fiber is 1.3 g/cm^3. The interfacial adhesion between the PVA fibers and the PP matrix was improved by a maleated PP. The Scona 6102 grade maleated polypropylene (MAPP) has an MFR of 25 g/10 min at 190 °C and 2.16 kg, a density of 0.91 g/cm^3, and a maleic anhydride content of >0.9 wt% was supplied by BYK Chemie GmbH (Wesel, Germany). The filler content of the composites was always 20 wt%, while that of the impact modifiers changed from 0 to 50 wt% in steps of 5 wt%. The amount of the coupling agent was 20 wt% calculated for the total amount of additives, *i.e.*, talc and/or PVA fiber. The composition of the materials prepared in the study is summarized in Table 1.

2.2. Sample preparation

PVA fibers were dried in a vacuum oven at 80 °C for 4 hours before processing. The components were homogenized in a Brabender DSK 42/7 twin-screw compounder (Brabender GmbH, Duisburg, Germany) with the set temperatures of 170–180–190–195 °C and at 40 rpm screw speed. Homogenization was repeated once to increase the homogeneity of the composites.

The granules prepared in the homogenization step were dried in a vacuum oven at 80 °C for 4 hours before processing and then they were injection molded into ISO 527-1A type 4 mm thick tensile bars [46] using a Demag Intelect 50/330-100 type injection molding machine (Sumitomo Demag, Schwaig, Germany). Processing parameters were 175–185–190–200 °C set temperatures, 600–1200 bar injection pressure, depending on modifier type and composition, 50 mm/s injection rate, 25 s holding time, and 30 s cooling time. Holding pressure was set at two-thirds of the actual injection molding pressure. The temperature of the mold was 40 °C.

2.3. Characterization, measurements

Specimens were stored in an atmosphere of 23 °C and 50% relative humidity for one week before testing. Tensile tests were carried out at 23 °C according to ISO 527-2 [47] using an Instron 5566 (Instron, Norwood, MA, USA) universal testing machine. Crosshead speed and gauge length were 5 mm/min and 115 mm, respectively. The impact resistance of the composites was determined using a Zwick Roell HIT5.5 apparatus with a 4 J hammer (Zwick Roell Group, Ulm, Germany) on specimens corresponding to the ISO 179-1eA standard [48] at 23 °C and 2 mm notch depth. Instrumented impact testing was carried out using the same apparatus with a 5 J hammer. Five parallel specimens were tested to determine the average value of the tensile properties and impact resistance of the materials, while instrumented impact tests were carried out on two specimens at each composition. The structure of the composites was characterized by scanning electron microscopy (SEM). Micrographs were recorded on the fractured surface of the specimens using a Jeol JSM 6380 LA apparatus (Jeol Ltd., Tokyo, Japan). Samples were immersed in liquid nitrogen for around 2 min before their fracture to avoid the considerable plastic deformation of the matrix. n-Hexane treatment was used to etch the elastomer particles from the fractured surfaces resulting in holes left behind. The broken surfaces were sputtered with gold before recording the micrographs.

3. Results and discussion

The results are presented in several sections. Mechanical properties (tensile and impact) are discussed in the first two sections, and then the structure of the two sets of composites are analyzed subsequently. The reinforcing effect, or the lack of it, of the two impact modifiers is shown next, followed by the discussion of general correlations and some consequences of the results for practice.

3.1. Tensile properties

One of the crucial properties of structural materials is their stiffness. Usually, the goal is the achievement

Table 1. Composition of the hybrid PP composites investigated in the study.

Composite	Talc content		Elastomer or PVA fiber content	
	[wt%]	[vol%]	[wt%]	[vol%]
PP/talc/elastomer	20	8	0, 5, 10, 15, 20, 25, 30, 40	0, 6, 12, 18, 24, 30, 36, 47
PP/talc/PVA fiber*	20	8	0, 5, 10, 15, 20, 25, 30, 40, 50	0, 4, 8, 13, 17, 21, 27, 37, 49

*composites were prepared with, and without MAPP, the amount of this latter was 20 wt% calculated for the total amount of additives.

of the largest possible stiffness for the production of parts with thin walls. The Young's modulus of the composites prepared is plotted against composition in Figure 1. Three correlations are plotted in the figure, one for the traditional impact modifier, the elastomer, and two for the new approach using PVA fibers as an impact modifier. In the latter case, the difference between the two sets of results is the application of a MAPP coupling agent to improve interfacial adhesion (full symbols, ●). Interactions cannot be improved this way in the elastomer-containing composite. The different behavior of the two additives is clearly seen in the figure. The addition of the elastomer decreases stiffness quite significantly, from about 3.7 GPa to around 1.5 GPa at 50 vol% elastomer content. It should be noted here that the matrix in this case, and in all other compositions, is PP reinforced with 8 vol% talc. The PVA fibers, on the other hand, increase stiffness slightly further from the value of the matrix to almost 5 GPa. Larger stiffness is more advantageous if it is accompanied by sufficient impact resistance. The coupling agent does not have much effect on modulus, but this result is in accordance with previous experience [49, 50], showing that stiffness is influenced only slightly by the strength of interfacial adhesion. It must also be mentioned that Young's modulus of semicrystalline polymers is affected by their crystalline structure. It was shown earlier [43] that especially talc but also PVA fibers have a nucleating effect in PP; their addition results in an increase in both crystallinity and lamella thickness. Despite the changes in the crystalline structure of the matrix, it has also been proved that the effect of this latter on stiffness and other mechanical properties is negligible compared to the direct effect of the modifiers and that of the dispersed structure. The same applies to the skin-core structure of the matrix polymer in injection-molded parts. The structure is complex, but it has a smaller effect on properties than additive content and dispersed structure. Moreover, all samples were prepared under the same injection molding conditions; thus, the processing-induced structure of the matrix should be similar as well.

The composition dependence of the tensile strength of the three sets of materials is shown in Figure 2. The elastomer also decreases the tensile strength of the PP/talc composite, as expected. The PVA fibers, on the other hand, have some reinforcing effect; tensile strength increases in both cases, only slightly in the absence of the coupling agent, and quite considerably at good adhesion. Obviously, the MAPP coupling agent improves interfacial adhesion significantly resulting in an increase in the load-bearing capacity of the fibers and thus in larger tensile strength. It is worth noting at this point that the reinforcing effect of PVA fibers is only moderate compared to that of traditional glass or carbon fibers. The reason for the

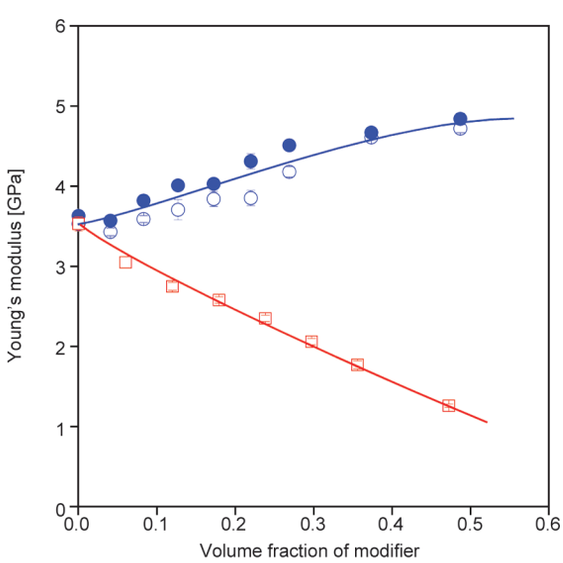

Figure 1. Composition dependence of the Young's modulus of PP hybrid composites impact modified in two different ways. Talc content: 8 vol%.
Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

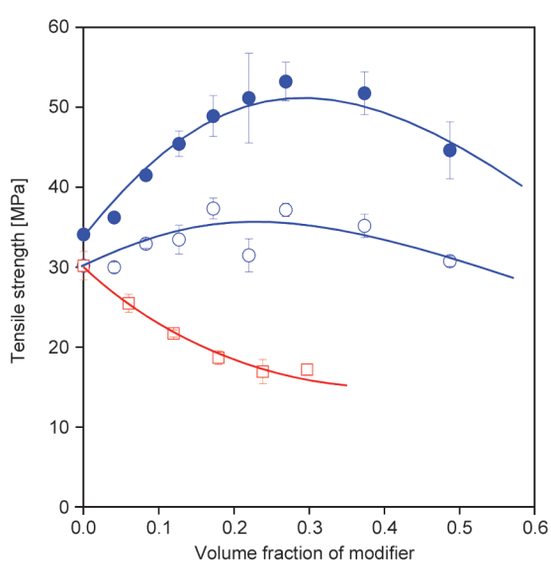

Figure 2. Tensile strength of PP hybrid composites plotted against the amount of impact modifier. Talc content: 8 vol%.
Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

smaller effect is that flexible polymer fibers easily turn and entangle with each other during processing leading to the formation of various fiber arrangements, such as bent, looped, twisted, knotted, and associated fibers [40]. Accordingly, the PVA fibers have complex orientation distribution, and they definitely do not align parallel to the wall of the injection molded specimens; therefore, they are able to carry only a relatively small part of the applied load. The maximum in tensile strength must be the result of the above-listed structural effects and possibly the changing orientation of the PVA fibers resulting in the decrease of strength at larger fiber contents.

The deformability of the composites is often related to their impact resistance. Elongation-at-break values are plotted against modifier content in Figure 3. The deformability of the composites containing the two modifiers had to be plotted on different scales because of their considerably differing values. The elongation of the PP/talc/PVA composites does not exceed 10%, while that of the materials containing the elastomer increases to around 450% at 30 vol% elastomer content. This large difference forecasts considerably differing impact resistances as well. The maximum in deformability in the PP/talc/PVA composites results from the structural effects mentioned above.

3.2. Impact resistance

As discussed in the introductory part, besides stiffness, one of the most important properties of structural materials is their impact resistance. The notched Charpy impact resistance of the composites is plotted against the amount of impact modifier in Figure 4. The correlations obtained are very similar to the composition dependence of the elongation-at-break values, supporting our statement about the relationship between the two quantities. Impact resistance increases only slightly up to 25 vol% elastomer content but achieves very large values, close to 80 kJ/m^2 at larger elastomer loadings. It should be noted here that stiffness decreases simultaneously with the increase of impact resistance. The considerable increase of both deformability and impact resistance observed at the elastomer content of 25–30 vol% must be related to local deformation processes. The effect of shear yielding initiated by the elastomer becomes very pronounced in this composition range, strongly influencing properties. The addition of PVA increases impact resistance more or less linearly from very small fiber contents up to the maximum, which is caused by the structural effects mentioned earlier. One could say that the elastomer is a much more efficient impact modifier than the PVA fibers, but we must call attention here to the fact that the targeted 15 kJ/m^2 impact resistance is achieved already at around 20 vol% PVA fiber content without the loss of stiffness.

Instrumented impact testing offers valuable information about the fracture process itself, about its two steps of crack initiation and crack propagation. The

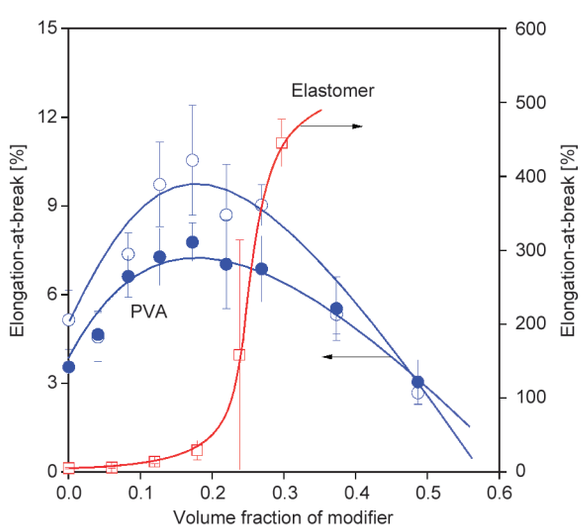

Figure 3. Deformability (elongation-at-break) of impact modified PP composites plotted as a function of composition. Talc content: 8 vol%.
Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

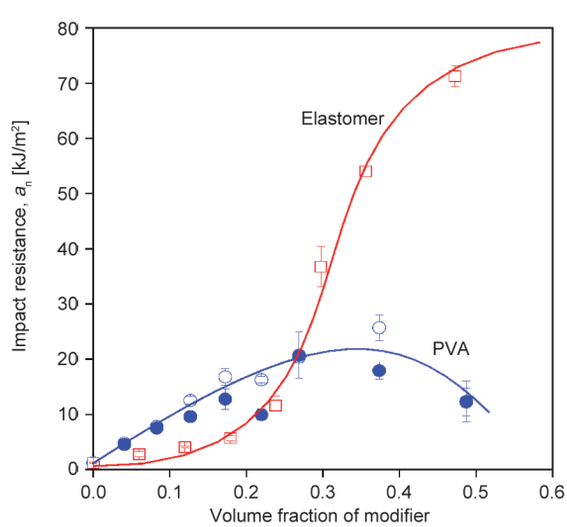

Figure 4. Dependence of the notched Charpy impact resistance of PP hybrid composites on the amount of the impact modifier. Talc content: 8 vol%.
Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

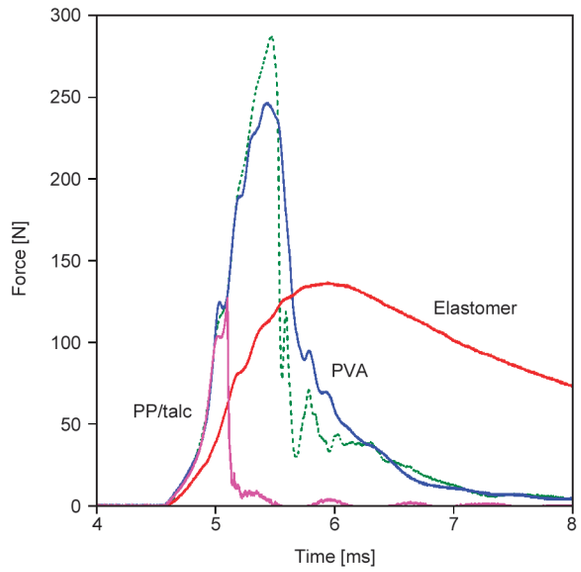

Figure 5. Instrumented impact testing of impact-modified hybrid PP composites. Talc content: 8 vol%. Impact modifier content: 27 vol% elastomer, 36 vol% PVA fiber.
Symbols: — without MAPP, - - - - with MAPP.

force *vs*. time correlation, *i.e.*, fractogram, of four materials is compared to each other in Figure 5. The PP talc composite fails in a brittle manner; both the force related to fracture initiation and the area under the trace corresponding to fracture energy are quite small. The elastomer changes the fracture process considerably. Catastrophic fracture does not occur, and crack propagation needs a constant input of energy. Crack initiation requires approximately the same force as in the matrix material. The shape of the fractogram corresponds to the expectation and agrees well with the results obtained in tensile and traditional impact testing (see Figures 3 and 4). PVA fibers, on the other hand, influence both the initiation and the propagation of the crack; both maximum force and the area under the trace increase considerably. The effect was shown to result from local deformation processes initiated by the fibers [40, 42]. The dominating process is debonding in the absence of the coupling agent and fiber fracture in its presence. The two processes absorb approximately the same amount of energy, although debonding and the subsequent plastic deformation of the matrix are more efficient in improving the overall impact resistance of PP composites [49].

3.3. Structure

As mentioned earlier, the structure of multicomponent PP composites can be quite complex, especially if one of the components is an elastomer. This latter may encapsulate the filler or fiber, or the components can be distributed separately in PP. Partial encapsulation may also take place, and the components might interact with each other in other ways as well, like the adsorption of one component on the other (PVA/talc). Talc particles are known to orientate parallel to the flow direction near the wall while randomly or perpendicular to it in the inner region of the injection-molded parts [51–53] because of the flow pattern of laminar mold filling. Orientation and orientation distribution affect properties; however, their effect is not significant in our case since both the amount of talc and processing parameters were kept constant during sample preparation. For the PVA fibers, other structural effects have also been mentioned, like changing orientation or the entanglement of the fibers [40, 42]. The recording of SEM micrographs is an efficient way to explore the structure of heterogeneous polymeric materials. However, the comparison is quite complicated in our case because of the dissimilar size of the individual components. The diameter of the PVA fibers is 11 μm, the average size of talc particles is around 6 μm, so many particles are much smaller, and the size of dispersed elastomer droplets are considerably below 1 μm. Accordingly, micrographs of different magnifications had to be prepared and must be compared in order to obtain a clear picture of the dispersed structure of our composites.

Selected micrographs recorded on the composites are presented in Figure 6. The micrographs showing the structure of the composites containing PVA fibers were recorded on the core, while images were taken on areas close to the wall in the case of the elastomer-modified composites. The flow direction in the mold was perpendicular to the plane of the images presented. The fracture surfaces of the composites containing the PVA fibers with and without MAPP are compared in Figures 6a and 6b at the same magnification. Talc particles are hardly visible in the micrographs; quite long debonded PVA fibers dominate the surface presented in Figure 6a. Changing local deformation mechanism is clearly shown in Figure 6b; the majority of PVA fibers fracture instead of debonding because of improved interfacial adhesion. The fractured surface of a PP/talc/PVA composite is shown in Figure 6c at larger magnification in order to see also the talc particles and their relation to the PVA fibers. According

to the micrograph, the fibers and talc particles are distributed independently of each other, and they do not interact in any way. The lack of interaction is quite understandable since interfacial interactions are not very strong between the two components. Figure 6d presents the surface of a PP/talc/PVA/MAPP composite in a similar magnification as in the previous case. The micrograph presents practically the same picture, independent distribution of talc and PVA, and additionally, one can see a fractured PVA fiber. Finally, it should be noted that both talc particles and PVA fibers have random orientation in the inner region of the specimens due to laminar mold filling.

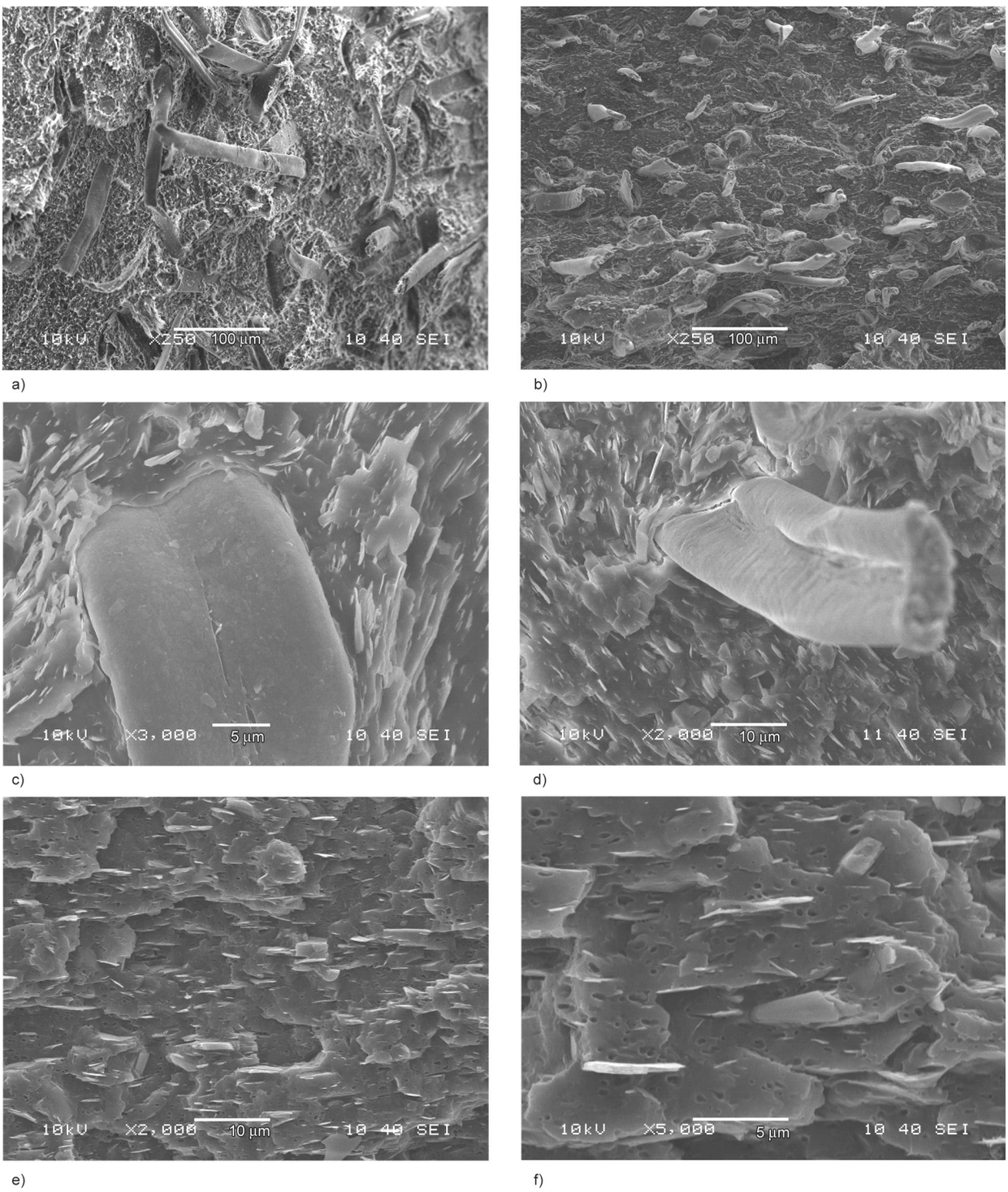

Figure 6. SEM micrographs recorded on the fractured surface of PP hybrid composites. The amount of talc is 8 vol%, while that of the elastomer and PVA fiber is 17 and 24 vol%, respectively. a) PVA, 250×, b) PVA/MAPP, 250×, c) PVA, 3000×, d) PVA/MAPP, 2000×, e) elastomer, 2000×, f) elastomer, 5000×.

The structure of PP composites impact modified with the elastomer is presented only at larger magnifications. Homogeneous distribution and the parallel orientation of talc particles to the wall of the specimens are seen in Figure 6e. This latter, together with our previous observations, offer unambiguous proof for the changing orientation of anisotropic particles along the cross-section of injection molded specimens. Dispersed elastomer particles are not visible in the micrograph at this magnification. The fractured surface of the same composite is shown in Figure 6f at larger magnification. The submicron-sized dispersed elastomer particles can also be seen in the micrograph in this case. A closer scrutiny also reveals that the elastomer droplets and the talc particles are distributed independently of each other in the PP matrix. Deformation and failure are determined by interfacial adhesion and local deformation processes.

3.4. Reinforcement

Although the visual observation of the primary results of mechanical testing offers qualitative information about the effect of various components on properties, quantitative comparison is impossible in this way; appropriate models must be used for the purpose. Such models describing the composition dependence of tensile strength [54] and impact resistance [55] have been developed earlier. The models take into account composition, structure, and interfacial interactions. The model for tensile strength is expressed as (Equation (1)):

$$\sigma_T = \sigma_{T0} \cdot \lambda^n \cdot \frac{1-\varphi}{1+2.5\varphi} \cdot \exp(B\varphi) \qquad (1)$$

where σ_T and σ_{T0} are the true tensile strength of the composite and the matrix, respectively, φ is the volume fraction of the dispersed component, B expresses load-bearing capacity, and it depends, among other factors, on interfacial adhesion. In the equation, true tensile strength ($\sigma_T = \sigma\lambda$, $\lambda = L/L_0$, relative elongation) accounts for the change in specimen cross-section due to deformation and λ^n for strain hardening occurring with increasing elongation. n characterizes the strain-hardening tendency of the polymer and can be determined from matrix properties. The model for fracture resistance considers the same factors but also the relative stiffness of the composites since impact resistance decreases with increasing stiffness. The model is described by Equation (2):

$$a_n = \frac{a_{n0}}{\frac{E}{E_0}} \cdot \frac{1-\varphi}{1+2.5\varphi} \cdot \exp(B\varphi) \qquad (2)$$

where a_n and a_{n0} are the notched Charpy impact resistance of the composite and the matrix polymer, respectively. The term accounting for strain hardening can be omitted here since deformations are small during fracture, but the stiffness of the material must be taken into account, as mentioned above. This effect is expressed by the term E/E_0, where E is Young's modulus of the composite, and E_0 is that of the matrix. The rearrangement of the equations results in reduced variables, *i.e.*, $\sigma_{Tred} = \sigma_T(1 + 2.5\varphi)/(1 - \varphi)/\lambda^n$ in the case of strength, and their plotting on the logarithmic scale should yield straight lines the slope of which expresses the effect of the dispersed component on the studied property.

The tensile strength of the three sets of composites was plotted in the way discussed above in Figure 7. Straight lines were obtained as predicted. The elastomer does not carry practically any load, as indicated by the slope of the line. At zero adhesion and load bearing, the slope of the line should be zero, but zero adhesion does not exist in practice. PVA, on the other hand, reinforces the PP/talc composite, and the beneficial effect of the coupling agent is also shown quite clearly by the different slopes obtained for the composites prepared with and without MAPP. The deviation of points at large PVA contents is caused

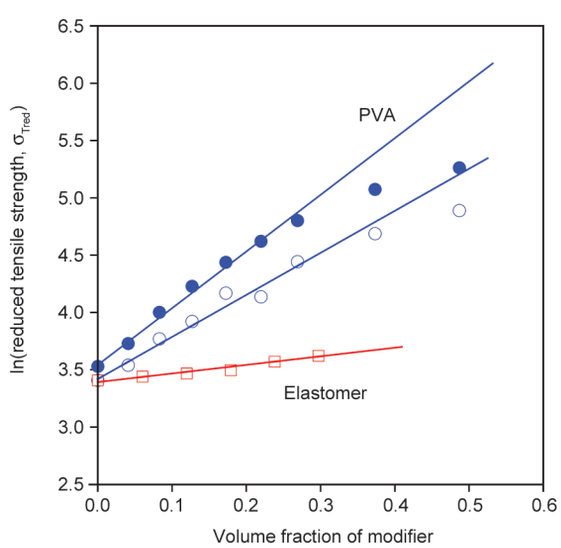

Figure 7. Quantitative determination of the effect of the impact modifiers on the tensile strength of hybrid PP composites according to the model represented by Equation (1). Talc content: 8 vol%.
Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

by the structural effects mentioned in previous sections (Sections 3.1 and 3.2).

The linear correlations for impact resistance are similarly good as those obtained for tensile strength, as shown in Figure 8. The parameters calculated by the fitting of the models to the experimental data are listed in Table 2. The determination of Parameter *B* allows the quantitative comparison of the effect of the two impact modifiers. As the parameters show, the load-bearing capacity of the elastomer is very small; parameter *B* is 0.71. The PVA fiber, on the other hand, reinforces the PP/talc composite, and the positive effect of coupling is also shown by the results. Rather surprisingly, the effect of PVA is also more beneficial for impact resistance, as shown by the *B* values calculated from that property. In accordance with previous results [42], the coupling is less advantageous in this case because the fracture of the PVA fibers absorbs less energy than debonding and the subsequent plastic deformation of the matrix. The decisive question is whether larger impact resistance or larger tensile strength is required for a given material; the use of coupling must be decided accordingly.

Table 2. Quantitative estimation of the effect (Parameter *B*) of the components used as impact modifiers in PP hybrid composites (see Equations (1) and (2)).

Modifier	Coupling	Interception	Parameter *B*	R^{2*}
Tensile strength [MPa]				
PVA	–	30.7	3.74	0.9685
PVA	+	34.7	5.07	0.9939
Elastomer	–	29.9	0.71	0.9614
Impact resistance [kJ/m^2]				
PVA	–	2.6	12.82	0.8913
PVA	+	4.2	9.40	0.9355
Elastomer	–	1.5	9.19	0.9918

*determination coefficient indicating the goodness of the fit.

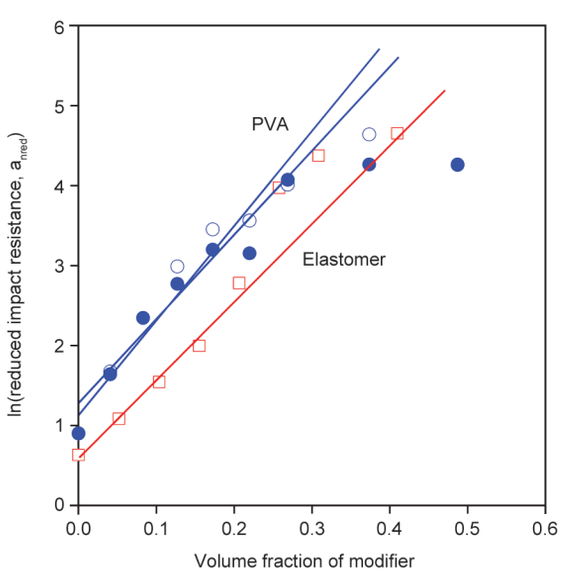

Figure 8. Quantitative comparison of the efficiency of two different impact modification approaches in hybrid PP composites with the help of the model represented by Equation (2). Talc content: 8 vol%. Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

3.5. Discussion, correlations

The results presented above prove that the impact resistance of PP reinforced with talc can be modified in various ways. The traditional approach of using an elastomer for the purpose becomes efficient only at large elastomer contents, but adding much elastomer to the polymer has considerable drawbacks, the most prominent one being the considerable decrease of stiffness. The new approach of adding synthetic polymer fiber is more beneficial in many ways, including those mentioned above. Structural effects do not play a role in the determination of properties; the components are distributed homogeneously in the PP matrix and do not interact with each other. Local deformation processes, on the other hand, are very important; the shear yielding of the matrix initiated by the presence of the elastomer particles consumes considerable energy as well as the plastic deformation initiated by the debonding of PVA fibers. The fracture of the fibers is less efficient in energy consumption and impact modification than debonding and plastic deformation.

Obviously, both approaches have advantages and drawbacks. However, one must consider the combination of properties obtained and the property profile of the material. As mentioned in the introductory part, often large stiffness and impact resistance are required from a structural material used primarily in the automotive sector. These two properties are plotted against each other in Figure 9 for the three sets of composites studied. This representation clearly shows the benefits of the new approach. The traditional impact modifier, the elastomer, increases impact resistance only slightly at small additive contents but decreases the stiffness of the polymer. Although very large impact resistances can be achieved at larger elastomer loadings, modulus decreases drastically. PVA fibers, on the other hand, increase both properties simultaneously, and the targeted property profile can be achieved at relatively small additive content.

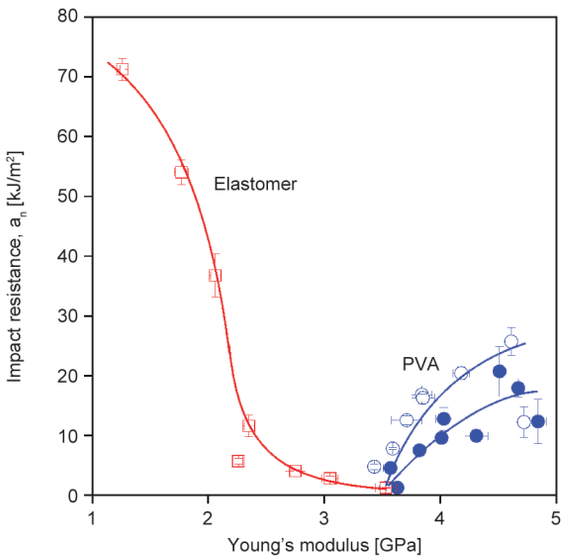

Figure 9. The Young's modulus and impact resistance of impact-modified hybrid PP composites plotted against each other. Combined effect of the additives on both properties. Talc content: 8 vol%. Symbols: □ – elastomer, ○ – PVA without MAPP, ● – PVA with MAPP.

Moreover, properties can be adjusted according to the requirements of the intended application; one can select between larger strength or larger impact resistance by the use of a coupling agent.

4. Conclusions

PP is a commodity polymer with an advantageous property profile, but the impact resistance of homopolymers is often not sufficient for a number of applications. Impact resistance can be modified in various ways. The analysis of the results obtained on PP hybrid composites reinforced with talc shows that the use of PVA as an impact modifier is more beneficial than that of an elastomer. The latter decreases stiffness quite considerably, does not carry practically any load, and even its impact modification efficiency is somewhat smaller than that of the PVA fibers. These latter, on the other hand, increase stiffness to some extent, and tensile strength considerably, especially in the presence of a coupling agent, and the targeted impact resistance can be achieved at moderate fiber contents. Structural effects do not play a role in the determination of properties, at least at small additive contents, which are relevant for practical applications. The positive property profile achieved, *i.e.*, the simultaneous increase of stiffness and impact resistance, is the result of the local deformation mechanisms occurring in the PP/talc/PVA composites. Properties can be further adjusted to purpose by the application of a functionalized PP coupling agent.

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