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RESEARCH ARTICLE

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# Improvement of the impact resistance of natural fiber–reinforced polypropylene composites through hybridization

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## Abstract

Polypropylene (PP) hybrid composites were prepared by the combination of natural reinforcements and poly(ethylene terephthalate) (PET) fibers. Wood, flax, and sugar palm fibers were used to increase stiffness and strength, while PET fibers served to improve impact resistance. Interfacial adhesion was increased by using a maleated PP (MAPP) coupling agent. The hybrid composites containing 20 wt% of the natural fibers were homogenized in a twin-screw compounder and then injection molded into standard tensile specimens. The amount of PET fibers was changed from 0 to 40 wt% in the composites. Tensile and impact testing, acoustic emission measurements, and scanning electron microscopy (SEM) were used for the characterization of the composites as well as to follow deformation and failure processes. The results proved that the concept of using PET fibers to improve impact resistance works with all natural fibers. Local deformations, the debonding or pullout of the PET fibers, initiate the plastic deformation of the matrix, which consumes considerable energy. The fracture of PET fibers might also contribute to energy absorption. The type of natural fiber does not influence the effect; the amount of PET fibers determines fracture resistance. The improvement of interfacial adhesion by coupling increases strength and slightly improves impact resistance. The overall properties of the hybrid composites prepared are acceptable, sufficiently large stiffness and impact resistance being achieved for a large number of structural applications.

**KEYWORDS**
acoustic emission testing, fiber fracture, impact resistance, natural fiber, strength

## 1 | INTRODUCTION

The demand of the industry for newer and better materials increases continuously resulting in constant research and development efforts to satisfy this demand. In the automotive[1,2] and the construction[3,4] industry, a large amount of plastics are used as structural materials because they are light, easy to process, and their price is reasonable. The requirement for such materials is often large stiffness but good impact resistance at the same time. However, inverse correlation exists between these two properties for most structural materials including plastics, metals, and ceramics,[5] thus the requirement is difficult to satisfy. Accordingly, numerous efforts are being made to

produce materials with large stiffness and impact resistance through the control of structure or by hybridization.[6-10]

Polypropylene (PP) is a polymer used in large quantities in the automotive industry because its stiffness is reasonable, it is light, its price is affordable, and it is easy to process.[2] On the other hand, the impact strength of PP homopolymers at the levels of melt flow rate (MFR) required for complex injection molding (i.e., MFR >10 g/10 min at 230°C/2.16 kg) is usually small, around 2 kJ/m$^2$, and even its stiffness must be increased for certain applications. PP can be modified in many ways, stiffness by the introduction of mineral fillers or fibers[11,12] while fracture resistance by the addition of elastomers.[13,14] However, neither of these modifications results in the simultaneous improvement of the two properties of interest, that is, stiffness and impact strength, to the extent required, because fillers and fibers increase stiffness,[15] but often decrease impact resistance, while elastomers have the opposite effect.[14] The solution to the problem is the simultaneous application of the two modifiers[16]; PP composites used for the production of bumpers often contain a filler or fiber and an elastomer at the same time, that is, they are hybrid materials.[6-9,17,18]

In the last two decades, considerable effort was done to improve the environmental impact of plastics, thus traditional glass and carbon fibers are being replaced with wood flour and natural fibers in many products.[19-22] Several components of cars, for example, consoles, door panels, hat racks, and so on contain wood or natural fibers as reinforcement.[23-25] Natural reinforcements have many advantages, they come from renewable resources, they are lighter than glass, cheap, and they have positive environmental impact,[26] but they have some drawbacks as well. The quality depends on the origin of the crop or even the time of the harvest, the fibers are sensitive to heat during processing, their adhesion to the polymer matrix is often poor, they absorb moisture and change dimensions, and so on.[27] However, one of their largest drawbacks is their poor strength in the transverse direction to their axis and the consequent small impact resistance of their composites.[28-30] Many attempts were made to vary the particle characteristics of wood, the properties of the matrix polymer, or interfacial adhesion by coupling, but the impact resistance of PP/wood composites remained small.[31-34] Even the use of a PP reactor blend containing as much as 33 wt% elastomer did not result in sufficient impact resistance,[31] this property remained always at a low level at least at large fiber contents. The fracture of wood particles and the cavitation of the matrix resulted in the premature failure of the composites and in inferior impact resistance.[31] Accordingly, the strategy used earlier, that is, the combined use of a filler or fiber and an elastomer impact modifier did not work in PP composites reinforced with wood flour or natural fibers.[31,35,36]

A solution for the problem was offered by the use of synthetic fibers together with the natural reinforcements. Hybrid composites containing wood as reinforcement and poly(ethylene terephthalate) (PET) fibers had a stiffness of 3 GPa and 15 kJ/m$^2$ impact resistance,[37] a combination of properties readily accepted in the automotive and construction industries. Stiffness improved as the result of the presence of the natural fiber, while PET fibers increased impact resistance.[37] The concept was checked and verified also in composites reinforced with traditional glass and carbon fibers.[38] Even better property combinations could be achieved in this way, stiffness as large as 6 GPa and impact resistance close to 15 kJ/m$^2$. However, the environmental benefit of using reinforcements from natural resources was lost in this latter case.

Accordingly, the goal of this study was to verify the validity of the approach of hybridization also for PP composites reinforced with natural fibers. Flax and sugar palm fibers (SPFs) were applied as reinforcements with wood flour being used as reference. The attention was focused less on conventional properties, stiffness, and strength but more on fracture resistance. Local deformation processes were analyzed to determine the mechanism of deformation and failure. The property profile of the materials produced was determined, and the possibilities for further improvement, as well as relevance for practice, are also discussed in the final section of the paper.

## 2 | EXPERIMENTAL

### 2.1 | Materials

The PP used as matrix in the experiments was the Daplen HJ 325 MO grade homopolymer (hPP) of Borealis GmbH, Austria, with an MFR value of 50 g/10 min (2.16 kg, 230°C) and a density of 0.91 g/cm$^3$. A PP functionalized with maleic anhydride (MAPP) was used for coupling to improve interfacial adhesion. The Scona 2112 grade with an MFR of 3.5 g/10 min (2.16 kg, 190°C) and MA content of 0.9–1.2% was obtained from Byk-Chemie GmbH, Germany. The amount of the functionalized PP was always 10 wt% in relation to the total amount of fibers.

Three fibers were used as reinforcements: wood, flax, and SPF. PET fibers were added to improve impact resistance. The wood fiber was obtained from Rettenmaier and Söhne GmbH, Germany, the average length of the particles was 363 μm, their diameter 64 μm, and thus the aspect ratio of the reinforcement was 6.8. The flax fiber was obtained from Hungaro-Len Kft., Hungary, as roving and it was cut to about 10–15 mm length to prepare the composites. The SPFs were obtained from a local producer in Sidoarjo, Indonesia, as bundles and were cut to the same length before homogenization. The particle characteristics of wood were determined by image analysis from scanning electron micrographs but also by digital optical microscopy (DOM) before and after processing. The dimensions of the reinforcing fibers are collected in Table 1. The original length of the PET fibers was 4 mm, and their diameter, 24 μm. The hybrid composites always contained 20 wt% of the reinforcing fiber (wood, flax, SPF) and the amount of the PET fibers changed from 0 to 40 wt% in 5 wt% steps.

### 2.2 | Sample preparation

The fibers and the polymer were homogenized in a twin-screw compounder (Brabender DSK 42/7, Brabender, Germany) at the set

**TABLE 1** Dimensions of the fibers used as reinforcement in hybrid PP composites at 20 wt% of the natural fiber and 20 wt% of PET; effect of coupling and processing

| Fiber | Coupling | Processing | Length (μm) | Diameter (μm) | Aspect ratio |
|---|---|---|---|---|---|
| Wood | – | Before | 363 ± 318 | 64 ± 42 | 6.8 |
| | – | After | 169 ± 94 | 52 ± 30 | 3.5 |
| | + | After | 180 ± 102 | 55 ± 4 | 3.6 |
| Flax | – | Before | 1000 ± 200 | 18 ± 7 | 55 |
| | – | After | 88 ± 54 | 17 ± 8 | 5.6 |
| | + | After | 81 ± 59 | 17 ± 8 | 5.0 |
| Sugar palm | – | Before | 1000 ± 200 | 150 ± 67 | 6.7 |
| | – | After | 211 ± 277 | 50 ± 62 | 4.6 |
| | + | After | 231 ± 317 | 71 ± 105 | 4.2 |

Abbreviations: PET, poly(ethylene terephthalate); PP, polypropylene.

peratures of 180–190–200–210°C and 40 rpm. The natural fibers were dried at 105°C for 4 h in an air-circulating oven before extrusion. Extrusion was repeated once in order to increase homogeneity. The granulated composites were dried at 80°C for 4 h, and then they were injection molded into standard (ISO 527 1A) tensile bars of 4 mm thickness using a Demag IntElect 50/330-100 machine (Demag, Germany). Processing parameters were 40–170–180–190–200°C set temperatures, 300–800 bar injection pressure, depending on fiber type and content, 50 bar back pressure, 50 mm/s injection speed, 25 s holding time, and 30 s cooling time. The temperature of the mold was set to 40°C. The specimens were stored at ambient temperature (23°C, 50% RH) for a week before further testing.

### 2.3 | Characterization and measurements

The mechanical properties of the composites were characterized by tensile and impact testing. Tensile tests were carried out using an Instron 5566 universal testing machine (Instron, USA) at a gauge length of 115 and 5 mm/min crosshead speed. Modulus, yield properties (yield stress and yield strain), tensile strength, and elongation-at-break were derived from recorded stress versus elongation traces. Local deformation processes were followed by acoustic emission (AE) testing. AE signals were recorded using a Sensophone AED 404 apparatus (Geréb és Társa Kft., Hungary). A single a11 resonance detector with the resonance frequency of 150 kHz was attached to the center of the specimen. The threshold level of detection was set to 23 dB. Impact resistance was characterized by the notched Charpy impact strength determined according to the ISO 179 standard at 23°C at 2 mm notch depth. Instrumented impact testing was carried out using a Ceast Resil 5.5 apparatus (Ceast SpA, Italy) with a 4 J hammer. The appearance of broken surfaces was studied by scanning electron microscopy (Jeol JSM 6380 LA, Jeol Ltd., Japan). Micrographs were recorded on fracture surfaces created during tensile and fracture testing, respectively. The possible attrition of the fibers was checked by DOM. Thin films of about 100 μm thickness were prepared by compression molding, and the dimensions of at least 200 fibers was measured on micrographs recorded on the films.

## 3 | RESULTS AND DISCUSSION

The results are discussed in several sections. Particle characteristics and the effect of processing on them are discussed first together with a brief presentation of tensile properties. Fracture resistance and its relationship to local deformation processes are analyzed next, while general correlations are discussed in the last section together with notes on practical relevance.

### 3.1 | Properties

The changes in fiber dimensions, that is, the attrition of stiff fibers during thermoplastic processing is a major issue in fiber–reinforced composites.[39] Injection molding is especially hard on stiff fibers, and, occasionally, the length of the fibers can decrease below the critical value thus losing most of the reinforcing effect.[40-42] Previous work showed that the length of PET fibers also changes, but not in an extent as that of stiff, reinforcing fibers. The original average length of PET fibers of 4 mm decreases to about 1–2 mm during processing.[42] However, the estimation of the real length of the fibers is difficult because they twist and even entangle with each other.[43] Since the role of PET fibers is not reinforcement but impact modification, their exact length is less important than that of the stiff fibers.

Fiber length and diameter before and after processing are listed in Table 1 for the natural fibers used in this study. Wood fibers are relative short, thus the extent of their attrition is not very large. Flax, on the other hand, was cut to a considerable size before homogenization and the decrease in its length is large, the fibers become quite short during processing. The diameter of these two fibers does not change very much. On the other hand, SPFs are quite large originally, and both their length and diameter decrease quite considerably. SPFs are the longest, followed by wood and flax, but their aspect ratio does not differ much, they are in the same order of magnitude. Mechanical properties and the reinforcing effect depend on the final dimensions of the fibers obtained after processing,[41] thus we must consider them during the evaluation of the results.

Tensile properties, notably stiffness, strength, and deformability are discussed only briefly. They all correspond to the expectations.

The stiffness of the composites containing only the stiff, reinforcing fibers at 20 wt% is moderate; it changes between 2.4 and 2.8 GPa. The addition of PET fibers increases modulus somewhat, but the reinforcing effect of this synthetic fiber is small, and the largest stiffness achieved in the presence of wood particles does not exceed 3.2 GPa. The deformability of all composites is limited changing between 2 and 8% and increasing slightly with increasing PET content. This latter effect might be important for impact, since fracture resistance increases with the increasing plastic deformation of the matrix polymer. Neither stiffness nor elongation depends much on coupling, that is, on the presence or absence of the MAPP coupling agent.[42]

Tensile strength is plotted against the amount of PET fibers in the composite in Figure 1. The difference among the composites containing the three stiff fibers is very small, hardly larger than the standard deviation of the measurement. Coupling, on the other hand, influences strength quite considerably. Tensile strength decreases with increasing PET content continuously at poor adhesion, in the absence of the coupling agent. True reinforcement is achieved when interfacial adhesion is good; strength increases to the acceptable level of about 40 MPa, irrespectively of the type of the stiff fiber.

## 3.2 | Fracture

Impact resistance is the crucial property of natural fiber reinforced composites. As mentioned earlier, it remained very small even if a large amount of elastomer impact modifier was added to the polymer.[31] The fracture strength of the natural fiber–reinforced hybrid composites is plotted against the amount of PET fibers in Figure 2. Impact resistance increases considerably with increasing PET fiber content from the small value of less than 2 kJ/m$^2$ to the respectable level of 15 kJ/m$^2$ at large PET content. The type of the natural fiber affects impact resistance only slightly at small PET content, but the difference increases with increasing amount of the synthetic fiber in the composite. Somewhat surprisingly, the largest impact resistance is achieved with wood fibers at good adhesion, and the smallest with flax in the absence of the MAPP coupling agent. A maximum exists in the composition dependence of impact strength indicating the effect of more than one factor or the presence of more than one process.

We hoped to obtain more information about the possible processes taking place during fracture by instrumented impact testing. Typical traces are presented in Figure 3 to demonstrate the effect of the amount of PET fibers on the fracture process. The traces were recorded on composites containing 20 wt% wood and increasing amounts of PET at good adhesion, that is, with MAPP. Fractograms are very similar for all the other combinations of materials, for the remaining two natural fibers with or without MAPP; only maximum force and the area under the trace change slightly as a function of these variables. The PP composite containing only wood particles fails by brittle fracture. Both maximum force and the area under the trace, that is, fracture energy increases with increasing PET content, indicating that both crack initiation and propagation are hindered by the presence of the synthetic fiber. At the largest PET content, fracture is not catastrophic showing the increased plastic deformation of the matrix initiated by the PET fibers. The exact mechanism might be revealed by the study of local deformation processes.

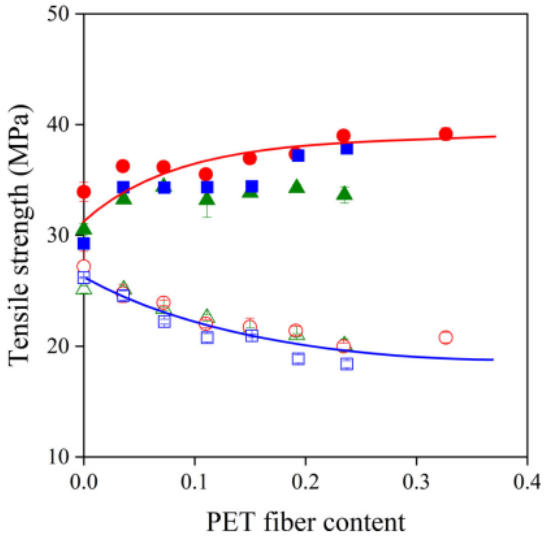


**FIGURE 1** Effect of PET fiber content on the tensile strength of hybrid PP composites. Natural fiber content 20 wt%. Symbols: (□,■) wood, (○,●) flax, (△,▲) sugar palm fiber; empty symbols: poor adhesion, without MAPP, full symbols: good adhesion, MAPP. MAPP, maleated PP; PET, poly(ethylene terephthalate); PP, polypropylene

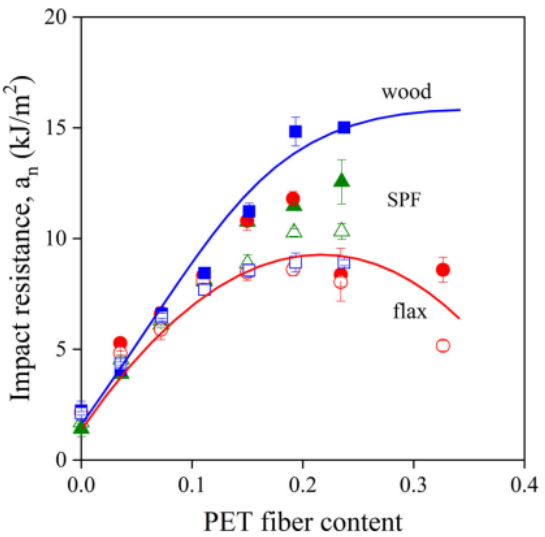


**FIGURE 2** Composition dependence of the impact resistance of hybrid PP composites. Natural fiber content 20 wt%. Symbols: (□,■) wood, (○,●) flax, (△,▲) sugar palm fiber; empty symbols: poor adhesion, without MAPP, full symbols: good adhesion, MAPP. MAPP, maleated PP; PP, polypropylene

### 3.3 | Local processes

The elastic properties of the matrix polymer and the fibers are different, thus an inhomogeneous stress field develops around the heterogeneities resulting in local stress maxima.[44,45] Deformation starts at these maxima inducing various local processes with different mechanisms.[45] In fiber–reinforced composites, the most frequent processes are debonding, fiber pullout, fiber fracture, and the shear yielding of the matrix.[46,47] The first three generate elastic waves, which can be detected by AE testing.[47] The result of such a test is presented in Figure 4A for the composite containing 20 wt% flax and 15 wt% PET fiber in the absence of the MAPP coupling agent. The small circles in the figure are individual acoustic events, while the continuous line (right axis) is the cumulative number of signal versus elongation trace. The stress versus elongation correlation is also plotted as reference. Individual signals can be divided into two groups. The majority of the events occurs at small deformation, that is, at small stress. Additional events take place at larger deformations and stresses, but their number is relatively small. Previous experience shows that the process occurring at small deformations in large numbers is usually debonding,[47,48] the separation of the fiber, and the matrix at the interface. The second process might be the pullout or fracture of the fibers.[28,29] The shear yielding of the matrix is not accompanied by acoustic activity.[47,48]

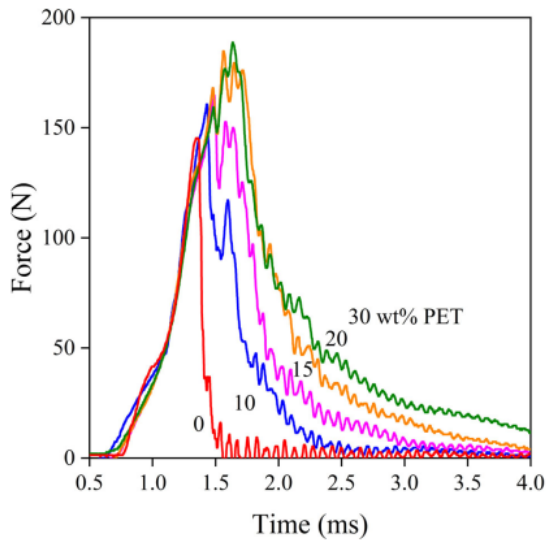


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**FIGURE 3** Instrumented impact testing of hybrid PP composites. The natural fiber is 20 wt% wood. MAPP was added for improved interfacial adhesion. Effect of PET fiber content. MAPP, maleated PP; PET, poly(ethylene terephthalate); PP, polypropylene

Different results are obtained in the AE testing of the composite containing the same ingredients in the same amount, but in the presence of the coupling agent (Figure 4B). The relative number of the two kinds of signals changes, less events occur at small and many more at large deformations. Increased interfacial adhesion must have changed the dominating deformation process from debonding to fiber pullout or fracture. The shape of the cumulative number of signal trace has also changed considerably, proving the modification of deformation mechanism. Changing interfacial adhesion modifies the number of acoustic events detected during the test as well.

The variation in acoustic activity and in the mechanism of deformation is demonstrated well by the comparison of the cumulative number of signal versus elongation correlations shown in Figure 5. In the absence of the coupling agent, the first process detected at small deformations dominates and much smaller number of events occur at large deformations. Wood composites show the largest acoustic activity, followed by flax, and the number of signals is surprising small for the composites containing the SPFs. The smaller activity results from the large diameter of these fibers, for which debonding stress is smaller thus the energy of the signals is also smaller, thus they are

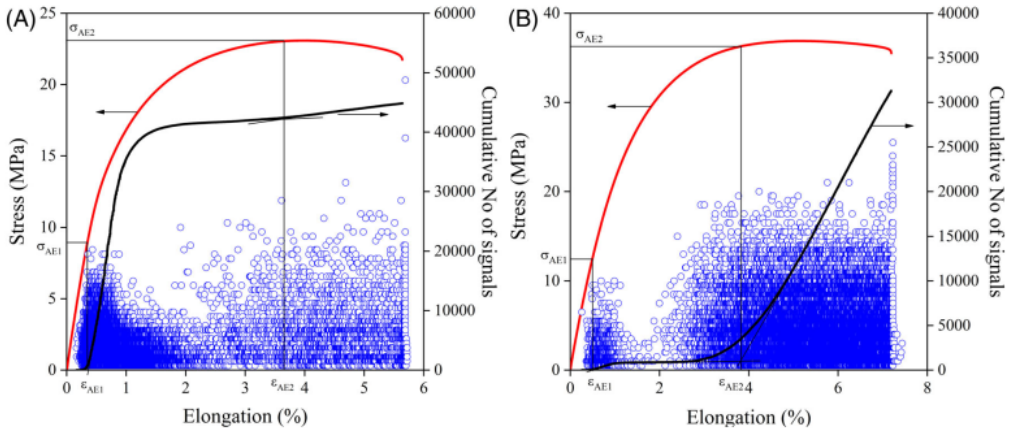


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**FIGURE 4** Results of the acoustic emission testing of a hybrid PP composite. Composition: 20 wt% flax, 15 wt% PET. Symbols: (○) individual acoustic signals, full lines: cumulative number of signal versus elongation (right axis) and stress versus elongation (left axis) correlation. (A) poor adhesion, no MAPP; (B) good adhesion, MAPP. MAPP, maleated PP; PET, poly(ethylene terephthalate); PP, polypropylene

mode difficult to detect. Moreover, because of the large size, the number of fibers is smaller at the same composition that further decreases the number of signals detected. However, the main processes are the same for all three fibers proven also by the similar shape of the cumulative number of signal versus elongation correlations (see Figure 5). At good adhesion, the shape of the traces changes completely.[28,29,47] Although the first process also occurs, it is not very easy to see because of the scale of the graph and the domination of the second process. The number of events decreases in all three cases and the order of acoustic activity remains the same as in the absence of coupling.

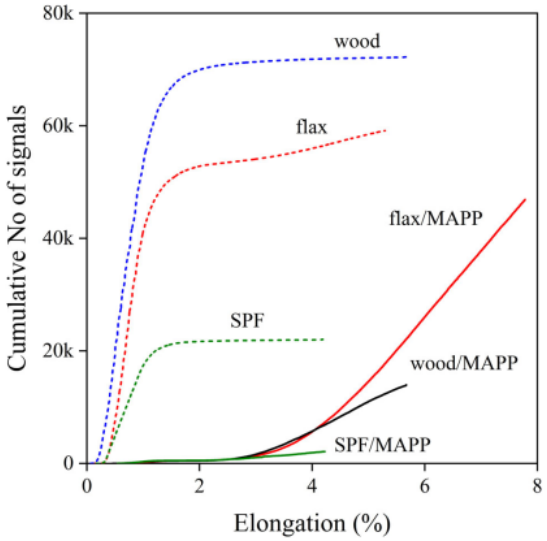


**FIGURE 5** Typical cumulative number of signal traces recorded on the hybrid PP composites containing various natural fibers with or without MAPP. PET content: 20 wt%. MAPP, maleated PP; PET, poly(ethylene terephthalate); PP, polypropylene

Based on AE testing, we can only speculate on the local processes taking place during deformation, but we cannot identify them with certainty. SEM micrographs may offer further information about the mechanism of these local deformation processes. Typical micrographs taken from the fracture surface of the various composites are presented in Figure 6. All the composites presented here contain 20 wt% of the reinforcing stiff fibers and 20 wt% PET. The micrographs are very similar in one respect: debonded or pulled-out PET fibers are visible in every micrograph in relatively large numbers irrespectively of the type of the reinforcing fiber or interfacial adhesion. A closer study of the micrographs reveal that these pulled out or debonded fibers are somewhat shorter at good adhesion, that is, depending on their orientation PET fibers also break during deformation. Wood fibers debond at poor adhesion (Figure 6A), while flax fibers fracture in the presence of the coupling agent (Figure 6D). A large SPF can be seen in Figure 6E, but it is difficult to decide if the fractured surface was created during cutting, processing, or testing. The SEM study confirmed our preliminary conclusions drawn from the results of AE testing that the deformation and fracture of the hybrid PP composites studied are dominated by the debonding, pull-out, or fracture of the PET fibers. Local deformation processes occur also around the reinforcing natural fibers, but they do not contribute to impact resistance (see Figure 2).

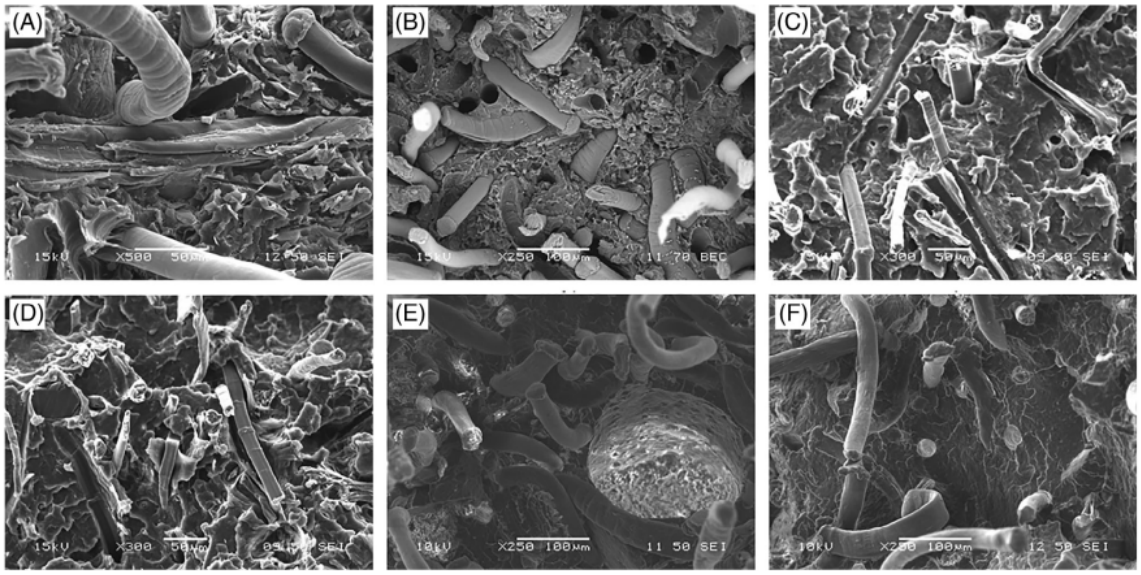


**FIGURE 6** SEM micrographs recorded on the fracture surface of hybrid PP composites. Composition: 20 wt% natural fiber, 20 wt% PET. (A) wood, no MAPP, (B) wood, MAPP, (C) flax, no MAPP, (D) flax, MAPP, (E) SPF, no MAPP, (F) SPF, MAPP. MAPP, maleated PP; PET, poly(ethylene terephthalate); PP, polypropylene; SEM, scanning electron microscopy; SPF, sugar palm fibers

### 3.4 | Correlations and discussion

The study of the properties, especially the impact resistance of the composites and the local deformation processes taking place during fracture, showed that local processes occurring around the stiff, reinforcing natural fibers do not contribute to energy absorption during fracture, but those around the PET fibers do. The relationship between the local processes and the final properties of the composites is demonstrated by Figure 7 quite well. Tensile strength is plotted against initiation stresses derived from the cumulative number of signal traces in the way shown in Figure 4A,B. The initiation of the first process, called AE1, does not result in the failure of the composite.[49] We assume that this process is debonding, and it dominates in the absence of the coupling agent.[49] At good adhesion, the second process (AE2) becomes more pronounced, and it leads to the immediate failure of the composite.[49] We assume that debonding and the subsequent plastic deformation of the matrix result in the increase of impact resistance, while the second process determines strength. Improved adhesion leads to the increase of debonding stress[50] and also to larger deformation, thus increasing impact resistance in spite of the smaller number of events (see Figures 2 and 5).

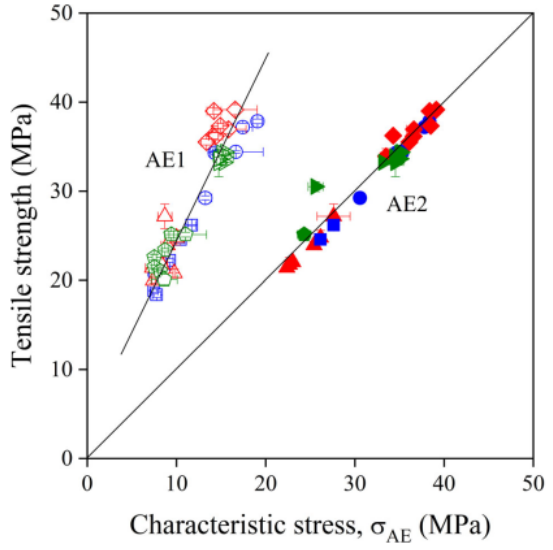


**FIGURE 7** Correlation between the initiation stresses of the local processes detected by acoustic emission testing and the tensile strength of hybrid PP composites. Symbols: (□) wood/AE1, (■) wood/AE2, (○) wood/MAPP/AE1, (●) wood/MAPP/AE2, (△) flax/AE1, (▲) flax/AE2, (▷) flax/MAPP/AE1, (▶) flax/MAPP/AE2, (⬠) SPF/AE1, (⬟) SPF/AE2, (◇) SPF/MAPP/AE1, (◆) SPF/MAPP/AE2. MAPP, maleated PP; SPF, sugar palm fibers

Reinforcement, impact resistance, and acoustic activity are compared in Table 2. Parameter $B$ in column three represents the reinforcing effect of the PET fibers. The parameter was derived from a model developed earlier, which can be expressed as

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

where $\sigma_T$ and $\sigma_{T0}$ are the true tensile strength of the composite and the matrix, respectively, $\varphi_f$ is the volume fraction of the fiber in the composite, $B$ expresses load-bearing capacity and it depends, among others, 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 and $\lambda^n$ for strain hardening occurring with increasing elongation. $n$ characterizes the strain hardening tendency of the polymer and can be determined from matrix properties. The rearrangement of the equation leads to the reduced tensile strength, and if we plot the natural logarithm of this latter against composition, we should obtain straight lines, the slope of which expresses the reinforcing effect of the fibers quantitatively.[51,52] PP containing the stiff, natural fibers is regarded as the matrix in this case. We can see that coupling improves interfacial adhesion and increases the reinforcing effect of the PET fibers quite significantly. The difference among the natural fibers is not very large; the best reinforcement is obtained with wood flour at good adhesion. Impact resistance is clearly dominated by the PET fibers, the type of the natural fiber not making any difference at all. Increased adhesion leads to larger impact resistance for the reasons mentioned above, that is, larger debonding stress, increased deformability, and plastic deformation of the matrix. Apparently, reinforcement and impact resistance are not related to acoustic

**TABLE 2** Some characteristics obtained by the mechanical testing of natural fiber-reinforced PP/PET hybrid composites; reinforcement, impact resistance, and acoustic activity

| Fiber | Coupling | Reinforcement parameter $B$ | Impact resistance[a] $a_n$ (kJ/m$^2$) | AE activity[a] no. of signals |
|---|---|---|---|---|
| Wood | – | 1.61 | 8.5 ± 0.3 | 71,700 ± 160 |
| | + | 3.94 | 11.2 ± 0.4 | 15,000 ± 2830 |
| Flax | – | 1.91 | 8.5 ± 0.4 | 61,200 ± 2320 |
| | + | 3.43 | 10.8 ± 0.4 | 41,000 ± 13,100 |
| Sugar palm | – | 2.08 | 8.9 ± 0.4 | 23,000 ± 760 |
| | + | 3.40 | 10.7 ± 0.2 | 2500 ± 950 |

Abbreviations: PET, poly(ethylene terephthalate); PP, polypropylene.
[a]At 20 wt% natural and 20 wt% PET fiber content.

activity at all. This characteristic, however, depends on a number of factors, like the number and size of the heterogeneities, the modulus of the composites,[53-55] and so on, making it difficult to find a direct correlation. Still, the results obtained on the two component PP/natural fiber composites show that these fibers also initiate events, but all evidence indicates that these events do not contribute to energy absorption, only those occurring around the PET fibers.

The hybrid composites studied in this work offer a reasonable compromise of properties. Although the reinforcing effect of natural fibers is not as large as that of the traditional glass or carbon fibers, their natural origin, better environmental impact like small carbon footprint, as well as lower price compensate for the loss of reinforcement. The impact resistance of natural fiber–reinforced PP composites is often quite small,[31] but it can be successfully compensated with the use of the synthetic fiber, PET in this case. A combination of 2.5 GPa modulus and 10 kJ/m$^2$ impact resistance can be easily achieved with these hybrid composites, which is quite acceptable in many structural applications in the automotive or the construction industry.

## 4 | CONCLUSIONS

The impact resistance of wood and natural fiber–reinforced PP composites is usually small and cannot be increased with the usual approach of adding elastomer impact modifiers. Impact strength was successfully improved in wood and in traditional, glass and carbon fiber–reinforced composites by the incorporation of PET fibers. This study proved that the concept works with other natural fibers as well; the impact strength of flax and SPF–reinforced composites could be also improved considerably. The mechanism of impact modification is always the same, the debonding or pullout of the PET fibers initiates the local yielding of the matrix, which consumes considerable energy. The fracture of PET fibers might also contribute to energy absorption. The type of natural fiber used as reinforcement does not influence the effect, and the amount of PET fibers determines the fracture resistance of the composites. Improving interfacial adhesion by coupling increases strength and slightly improves impact resistance. The overall properties of the hybrid composites prepared are acceptable, sufficiently large stiffness and impact resistance can be achieved for a large number of structural applications. In all probability, further improvement of properties can be achieved by the optimization of component selection, composition, and interfacial adhesion.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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