



## Polyethylene green composites modified with post agricultural waste filler: thermo-mechanical and damping properties

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### ABSTRACT

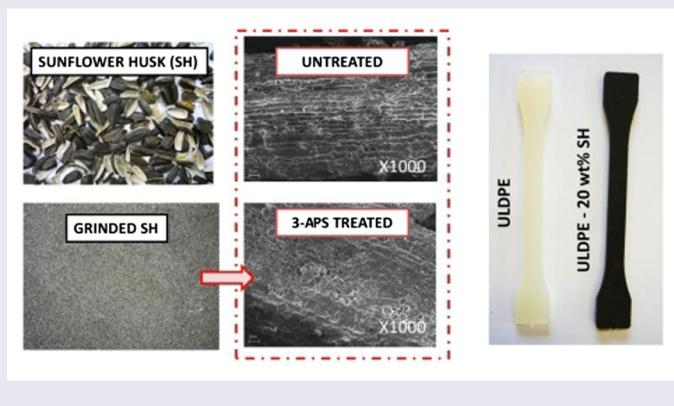
The aim of the study was to determine thermo-mechanical properties and applicability of sunflower husk waste as a filler for ultra low density polyethylene composites. The post agricultural waste filler was milled and chemically treated with (3-aminopropyl)triethoxysilane (3-APS). The amount of filler used was 5, 10 and 20 wt%. The mechanical and thermal properties of the composites containing unmodified and modified natural fillers were determined in the course of static tensile test, rebound resilience by Schob method, and dynamic mechanic thermal analysis. The influence of filler loading and chemical modification of the filler on the morphology of natural composites was evaluated by SEM analysis.

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## Introduction

An increasing use of commodity polymers is caused mainly by growing demands of the modern population. Moreover, the rising impact of plastic products on the development of human life standard is strongly connected with a long term expansion of petroleum based

polymers. Despite many attempts at applying bio-based and biodegradable polymers to commercial and industrial use, there are serious limitations caused by their properties as well as their shortage on the market. At the same time however, reduction of petroleum polymers use due to strong restrictions concerning their storage and product end-life cycle performance has gained ground among scientists [1–5]. For many years one of the most promising directions in the non-biodegradable polymeric material reduction and creating eco-friendly materials has been production of natural fiber composites (NFC) [2,3,6]. In literature there have been many studies focusing on the development of new composites containing both long and short natural fibers, such as: bamboo, jute, flax or kenaf [7–9]. It was proved that mechanical properties of accurately processed NFC based on polyolefin matrix may be compared to glass fiber reinforced plastics [10]. Because of their high availability, good mechanical, thermal and processing properties, as well as low price, polyethylene and polypropylene are the most popular polymeric materials used as a matrix for NFC. Due to their hydrophobic nature it is necessary to use different ways of surface modification of the hydrophilic natural fibers or grafting methods [10] including: silanization [11,12], mercerisation [13] of the fibers or incorporation of maleic anhydride as a coupling agent [14].

Silanes are commonly use as efficient coupling agents in polymer composites with fibrous [15–17], mineral filler [18] or organic and inorganic filler [19,20]. In order to obtain good connection of the fillers with polymer matrices, the silane molecule should have bifunctional groups which may respectively react with the two phases and forming a bridge between them [15]. Silane coupling agents structure may be described by the following pattern  $R_{(4-n)}-Si-(R'X)_n$  ( $n = 1,2$ ) where  $R$  is alkoxy,  $X$  represents an organofunctionality, and  $R'$  is an alkyl bridge (or alkyl spacer) connecting the silicon atom and the organofunctionality. Ishak et used two types of coupling agents such as 3-aminopropyltrimethoxysilane and 3-aminopropyltriethoxysilane for modification of oil palm empty fruit bunch and then production high-density polyethylene composites [21]. Addition of 1% both coupling agents increased significantly the tensile modulus and impact strength of the composites [21]. Also, in work [22] 3-aminopropyltriethoxysilane (3-APS) has been used as a coupling agent in the blends of natural rubber and low-density polyethylene with rice husk. The incorporation of rice husk treated with 3-APS has produced composite with improved tensile strength, Young's modulus, hardness and impact strength in comparison with untreated one [22]. Jayamol et al. described chemical modification of the pineapple leaf fiber with vinyltris(2-methoxyethoxy)silane and  $\gamma$ -aminopropyltriethoxysilane and their application in polyethylene composites. The strength and modulus of silane-treated composite were higher as compared to untreated composites [23]. Authors explain this effect by better stress transfer due to increased fiber-matrix adhesion in a silane-treated composite. Deepthi et al. used fly ash cenospheres grafted 3-aminopropyltriethoxysilane as reinforcing filler in high density polyethylene (HDPE) to develop lightweight composites. It was proved that both surface modification of cenospheres accompanied by compatibilization by dibutyl maleate led to the substantial improvement to mechanical properties and thermal stability of the composites [24]. Similar effect was described by Chand et al. [25]. Authors used cenospheres treated by octadecyltrichlorosilane as a filler for HDPE. The wear resistance, density and impact strength of these composite increased with silane treatment of cenospheres [25]. The results of the work [26] prove that the use of propyltrimethoxysilane as a coupling agents leads to higher fiber-matrix interactions in HDPE composites with slate fiber and has a positive effect on overall mechanical properties [26]. Methods of chemical modification to

increase surface adhesion between lignocellulosic fibers and hydrophobic polymers have been presented in works [27,28]. Hydrophilic behavior of the fiber have been decreased as a result of the reaction of silanol groups with hydroxyl groups on the surface of natural fibers and create chemical bonds with the fibers [15,29]. Composites of vinyltrimethoxy silane grafted HDPE and wood flour showed higher stiffness, tensile strength, elongation at break compared to the non-crosslinked composites [27]. Abdelmouleh et al. described chemical surface modification of cellulose fibers were after involving three silane coupling agents, namely  $\gamma$ -methacryloxypropyltrimethoxy- (MPS),  $\gamma$ -mercaptoproyltrimethoxy- (MRPS) and hexadecyltrimethoxy-silanes (HDS) [28]. Composite materials prepared using both matrices (low density polyethylene and natural rubber) and cellulose fibers treated with MPS and MRPS displayed good mechanical performances.

Currently, except for fiber-like natural fillers, great attention is placed on the incorporation of post-agricultural waste materials into polymeric matrix. Lignified oil plants waste, such as shells and husks, may be used not only as a source of biomass but also as low cost particle sized fillers for polymer composites after specific treatment including grinding and sieving [3,30]. Sunflower (*Helianthus annuus*) is the most cultivated oil-plant whose harvests remain at the level of 40  $T_g$ , where more than 50% of the sunflower seed is husk [31]. In literature several authors have discussed the possibility of the development of thermoplastic and thermoset composites filled with sunflower husk (SH) waste [31–36]. As it was presented by Salasinska et al., the application of ground SH as a filler for polyethylene composites allows to produce composite materials with improved mechanical properties [33]. Samples containing SH as a filler were characterized by higher water absorption in comparison to composites modified with fillers produced from other types of agricultural waste, such as finely-ground peanut hulls or pistachio shells [30].

Despite extensive studies in the field of SH and stalk waste application as fillers for polymeric composites, there has been no characterization of the thermoplastic elastomeric composites filled with this type of filler so far. The aim of this study is to determine mechanical, thermo-mechanical properties and structure of ultra low density polyethylene as a thermoplastic elastomer (TPE) matrix filled with SH powdered waste composites, and its potential applications.

## Experimental

### Materials

A commercial grade of ultra low density linear polyethylene copolymer (ULDPE) Attane SL4102G with the melt flow rate (MFR) of 1 g/10 min (190 °C, 2.16 kg) from the Dow Chem. was used in our experiments. The selected polymeric matrix was characterized by a low modification level.

SH was preliminary dried for 3 h within the temperature of 105 °C before milling. The milling process was conducted by means of Retsch Grindomix GM200 knife high speed grinder. Each grinding process was realized with the cutting knife rotary speed of 3000 rpm within the time of 2 min. Fractionation of ground SH was carried out by means of Firtsch Analysette 3 Pro sieve shaker equipped adequately with sieves with 600  $\mu\text{m}$  mesh size. Sieving process was realized with the amplitude of 2 mm within the time of 5 min.

Part of the organic filler was chemically modified by 3-aminopropyltriethoxysilane (3-APS), delivered by Sigma Aldrich. Before silane treatment natural ground filler was dried

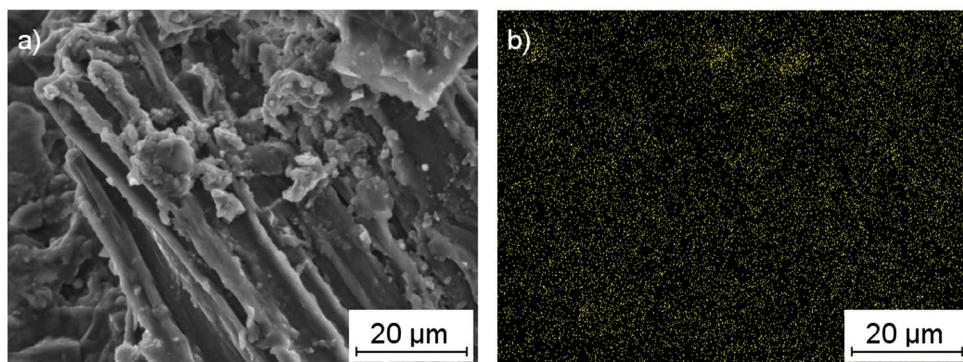
for 24 h. at 80 °C. 3 wt% of 3-APS, corresponding to weight percentage of filler, was hydrolyzed in a 50:50 v/v mixture of ethanol and water. After that unmodified and preliminary dried SH was incorporated into a solution of ethanol-water containing 3-APS and stirred for 3 h by a mechanical mixer, with the rotating speed of 500 rpm. Then SH was cast on a flat surface and dried at 75 °C for 24 h in order for ethanol and water to evaporate [11,12,37].

The ground, fractionated with 600 µm sieves and chemically modified sun flower husk was analyzed by scanning electron microscopy (SEM), with simultaneously realized energy dispersive X-ray measurement. In Figure 1 SEM image (a) and silicon atoms distribution (b) of the modified with APS (SHs) powdered organic fillers are presented. Silicone atoms in Figure 1(b) are represented by yellow dots. Presented EDS analysis confirms presence of the silane coupling agent on natural filler surface. It can be stated that the structure of the SHs filler surface became well covered with the silane coupling agent.

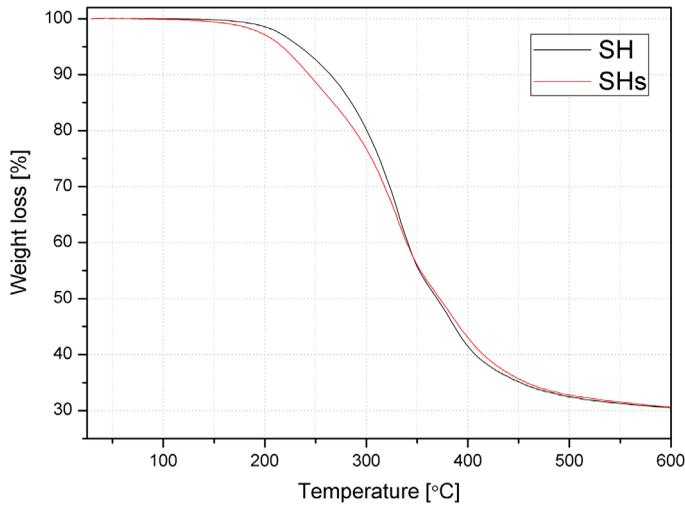
Both filler types were analyzed in order to determine their thermal stability as a reference to polyethylene processing conditions. The thermal properties were determined by thermogravimetric analyses (TGA) with temperatures set between 30 and 900 °C at the heating rate of 10 °C/min under nitrogen atmospheres, using a TG 209 F1 Netzsch apparatus. Approximately 5 mg samples were placed in ceramic pans. The TGA results showing the effect of surface modification on thermal stability of organic fillers in inert gas atmosphere were presented in Figure 2. It should be noticed that the chemically modified filler (SHs) displayed a lower thermal stability in comparison to the unmodified filler. However, thermal stability of both materials allowed for their use as ULDPE fillers with no risk of degradation during processing in a molten state.

### Sample preparation

The ULDPE pellets were milled into irregular powder with a Tria high-speed grinder. Prior to processing, both filler types were dried in vacuum for 3 h at 80 °C. The polymeric powder was mixed with SH and SHs in a rotary mixer Retsch GM 200 for 3 min with the rotation speed of 3000 rpm. The homogenization of the premixed blends with different filler concentrations (5, 10 and 20 wt%) was realized in the course of molten state extrusion, using a Zamak 16/40 EHD co-rotating twin screw extruder operating at 180 °C and 100 rpm. The screw's geometry was configured for processing of filled polyolefins. The extruded rod



**Figure 1.** SEM image (a) and distribution of silicon atoms through surface of modified filler (SHs), magnification  $\times 2000$ .



**Figure 2.** TGA curves of unmodified and modified SH.

was cooled in a water bath and then pelletized. After granulation, ULDPE and ULDPE composites were formed by injection molding after preliminary drying in vacuum (3 h at 80 °C). Samples described in ISO 527 were prepared with Engel ES 80/20HLS injection molding machine in the processing temperature of 180 °C, injection speed of 100 mm/s, holding pressure 5 MPa and cooling time 45 s. The rebound resilience circular disk-like samples with the thickness of 6 mm were compression molded using a Remiplast hydraulic press at 180 °C for 10 min with molding pressure of 18 MPa.

## Methods

Tensile testing was used to study the elastic modulus, elongation at break and yield strength of polyethylene and polyethylene-based composites. The tensile tests were performed as per ISO 527 with a Instron 4481 tensile tester at room temperature. The elastic modulus measurements were conducted at the crosshead speed of 1 mm/min, while elongation at break and tensile strength were carried out at 100 mm/min. Presented tensile test results are arithmetic mean calculated from 15 measurements.

The rebound resilience was determined with a Schob type pendulum Zwick 5109 in accordance with the ISO 4662 standard. Each evaluation was prepared for 7 test specimens.

The dynamic mechanic thermal analysis (DMTA) test was performed using the Anton Paar MCR 301 rheometer equipped with a torsion DMA measuring tool. Investigations were carried out with a constant frequency of 1 Hz and the strain of 0.01%. All samples were cooled down to -140 °C and heated up to 100 °C with the temperature ramp of 2 °C/min.

The injection molded samples' brittle fractures were examined and digitally captured using a scanning electron microscope (SEM) Zeiss Evo 40. The electron accelerating voltage of 12 kV was applied. Prior to the tests, all the specimens were sputtered with a layer of gold. Analysis of silane dispersion at surface of SHs filler was studied using SEM (Vega 5133MM, Tescan) with simultaneously realized silicon distribution mapping prepared by energy dispersive X-ray measurements. The magnifications of 500× and 2000 were used.

## Results and discussion

The results of tensile test experiments are presented in Figure 3. The set up of elastic modulus  $E$ , tensile strength  $\sigma_M$  and elongation at break  $\mathcal{E}$  values of ULDPE, as well as composite samples filled with SH and SHs were depicted on separate graphs. It was found that the incorporation of unmodified and modified organic waste fillers caused similar changes to the mechanic behavior of the composites. The application of little amounts of the organic filler (i.e., 5 wt%) resulted in a decrease of the elasticity modulus. For polyethylene modified with 20 wt% of the filler, the  $E$  values became higher than those measured for pure polyethylene samples. The main difference between composites filled with various organic waste fillers could be observed for samples containing 10 wt%, where SH incorporation led to a decrease of Young's modulus. The SHs in turn displayed an improved stiffness of the material in comparison to the ULDPE reference sample. ULDPE composites containing SHs exhibited higher values of Young's modulus and tensile strength in comparison to those modified with SH. It is noteworthy that no significant reduction of tensile strength was observed after SHs introduction into polyethylene matrix, whereas all samples filled with SH revealed decreased tensile strength in comparison to pure ULDPE. This phenomenon may be attributed to a weak interface interaction between hydrophilic unmodified organic filler and hydrophobic polyolefin matrix. An improved elongation at break was observed for all composites however, for samples filled with SHs higher values of  $\mathcal{E}$  were observed which could result from an improved adhesion between polymer and organic waste particles.

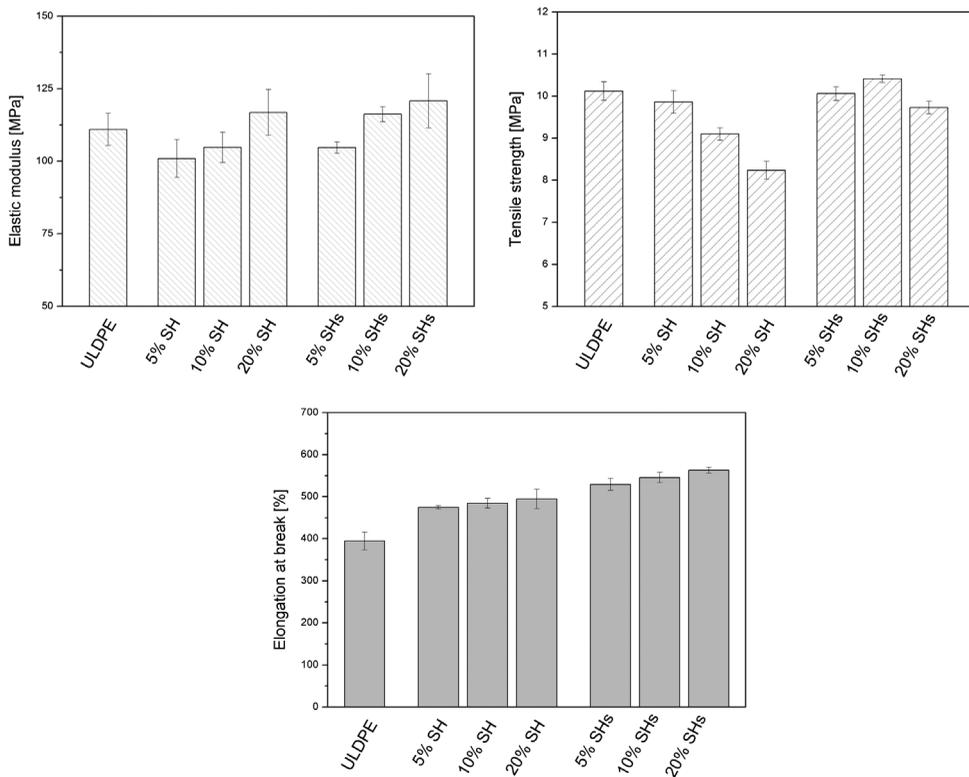


Figure 3. Mechanical properties obtained from static tensile test of pure ULDPE and ULDPE composites.

The values of rebound resilience  $R$  as a function of unmodified and modified filler amount are presented in Figure 4. It can be observed that an increasing content of the sunflower waste particles caused gradual decrease of  $R$ . This phenomenon is connected to the improved absorbance of the material [38]. The lower rebound resilience of the composite materials may be attributed to a partial presence of micro voids on the surface of the filler caused by gasification of the partially decomposed organic material or residual moisture which remained in the sunflower waste despite previous drying. Moreover, higher mechanical damping ability results from high amount of the natural filler which is characterized by good damping properties as a result of its complex structure. There is no significant difference between the results obtained for samples modified with various amounts of the introduced SH and SHs fillers. It can be stated that the incorporation of SH led to improved damping behavior of the composite materials in comparison to unmodified ULDPE with impact load.

Plots of the storage modulus  $G'$ , loss modulus  $G''$  and damping factor  $\tan\delta$  vs. temperature  $T$  for pure ULDPE and composites containing 20 wt% of SH and SHs are shown in Figure 5. According to literature, dynamic mechanical analysis of polyethylene allow to determine three peaks named as:  $\alpha$ -,  $\beta$ - and  $\gamma$ -transitions.  $\alpha$ -relaxation peak, observed usually between 20 and 60 °C, originates from polyethylene crystals motions caused by deformations within interfacial regions, which are activated as a result of chain mobility in the crystals.  $\beta$ -relaxation, which occurs in the temperature range between -35 and -5 °C, is commonly attributed to amorphous phase and the motion of branches in amorphous matrix.  $\gamma$ -relaxation is observed below -100 °C and intensity of the peak decrease with increasing density of polyethylene matrix. It is stated that  $\gamma$ -relaxation is mainly connected with amorphous phase of polyethylene and strongly dependent of the motion of a short chain segments [40]. It can be seen that the incorporation of organic waste filler improved the samples' stiffness in a wide temperature range (-135 to 80 °C). The difference between composite samples containing unmodified (SH) and modified (SHs) fillers in the values of  $G'$  is negligible. This fact is understandable because the storage modulus, which corresponds to elasticity

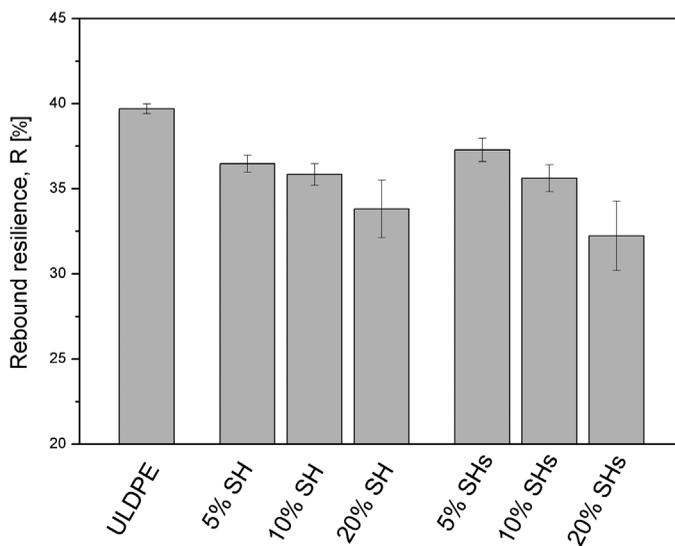
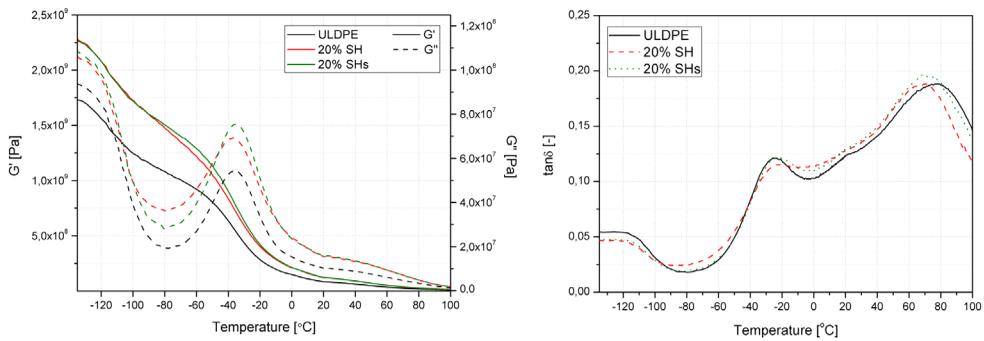


Figure 4. Rebound resilience of ULDPE and ULDPE composites.

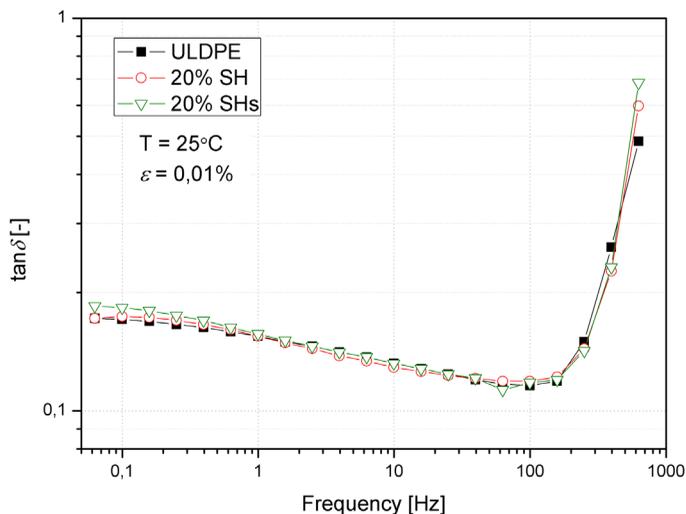


**Figure 5.** Storage modulus ( $G'$ ), loss modulus ( $G''$ ) and loss factor ( $\tan\delta$ ) vs. temperature of ULDPE and ULDPE composites containing 20 wt% of filler obtained by DMTA.

of the sample, is not a sensitive function of the interfacial adhesion [39]. In case of  $G''$  vs.  $T$  curve, composite samples reveal higher values of  $G''$  at peak at  $\beta$ -transition in comparison to pure ULDPE. Changes in the relaxation temperature values may be observed at both curves  $G''$  and  $\tan\delta$  vs.  $T$ . However,  $G''$  vs.  $T$  curve gives more distinct information about relaxation changes caused by incorporation of natural filler. Glass transition temperature ( $T_g$ ) was measured at peak of  $G''$  curve in the region of  $\beta$ -relaxation [40]. Following  $T_g$  values were determined:  $-35.5$  °C for ULDPE,  $-36.9$  °C for composite sample containing 20 wt% of SH and  $-35.4$  °C for composites filled with 20 wt% of SHs. Decrease of the  $T_g$  observed for 20 wt% SH sample may be attributed rather to insufficient interfacial adhesion between polymer and filler [41], than to plastifying effect of lignocellulose, which is a part of natural filler. Lowered  $\tan\delta$  values, measured at peak of  $\tan\delta$  vs.  $T$  curve near  $\beta$ -transition, for composites containing 20 wt% of SH are related to reinforcing effect of organic filler. Incorporation of unmodified particle shaped filler reduced damping properties of composite material in comparison to pure polymer and composite containing silanized SH waste. The difference between composites filled with unmodified and modified filler results from lowered compatibility of composites containing SH in comparison to SHs. Moreover, wider transition range of both composites, obtained during sample heating, near  $\beta$ -transition temperature may be attributed to lower thermal diffusivity in comparison to ULDPE. No significant changes in  $\alpha$ - and  $\gamma$ -relaxation caused by incorporation of filler were noted.  $\gamma$ -relaxation of composites was observed at similar temperature values for all considered materials (below  $-115$  °C), moreover horizontal shift of the  $G''$  and  $\tan\delta$  curves corresponds to changes of material stiffness. Lowered intensity of  $\tan\delta$  peak denoted at  $22$  °C ( $\alpha$ -relaxation) for composite samples is related to lowered crystallinity of composite samples in comparison to pure polymeric matrix. Preliminary realized differential scanning calorimetry (DSC) analyses exhibited that incorporation of the SH into ULDPE matrix caused suppressed crystallization of linear polyethylene copolymer. Lower softening temperature of composite materials read out from peak of  $\tan\delta$  vs.  $T$  curve, observed between  $60$  and  $80$  °C, indicates that both types of the composite materials are characterized by a narrower application range at elevated temperature in comparison to pure ULDPE. Mentioned peak is corresponding to melting of octane being a part of ULDPE copolymer. Moreover, this difference may be attributed to a decreased amount of polymeric material in a composite and changes of composite material melting behavior.

A comparison of  $\tan\delta$  values measured at constant room temperature as a function of the strain frequency for pure ULDPE and ULDPE composites modified with 20 wt% of SH and SHs is presented in Figure 6. It can be seen that there are no significant changes in damping behavior caused by the incorporation of the organic waste filler in the low frequency excitation range. However, at higher frequency values, i.e., 500 Hz, the differences between pure ULDPE samples and composite materials became significant. The highest values of damping factor were observed for the sample containing 20 wt% of SHs, and the lowest for the pure ULDPE. The results of the frequency sweep test are in good agreement with the results of the rebound resilience experiment. Therefore, it can be stated that composites based on the ULDPE, used as a TPE and containing SH as a filler reveal a tendency to dissipate mechanical energy during impact load and dynamic excitations at high frequencies.

SEM images analysis allows to evaluate dispersion of the organic filler in polymeric matrix as well as interface adhesion. A set up of photographs presenting polyethylene and polyethylene composites containing from 5 wt% to 20 wt% of the SH and SHs is shown in Figure 7. Structure analysis of the composites containing unmodified and modified fillers gave a deeper insight into the influence of chemical treatment on the improved dispersion and adhesion between 3-APS modified SH and ULDPE. It can be observed that for samples containing 20 wt% of SH some voids occurred on the fractured composite sample surface as an effect of pulling out of organic filler particles from the polyethylene matrix due to a weak interfacial interactions. For samples containing SHs as a filler no voids were observed. Moreover, in the microphotographs of the composites containing 10 wt% and 20 wt% of the SHs better dispersion of the filler may be observed than for samples containing unmodified SH.



**Figure 6.**  $\tan\delta$  of ULDPE and ULDPE composites containing 20 wt% of filler as a function of frequency at 25 °C.

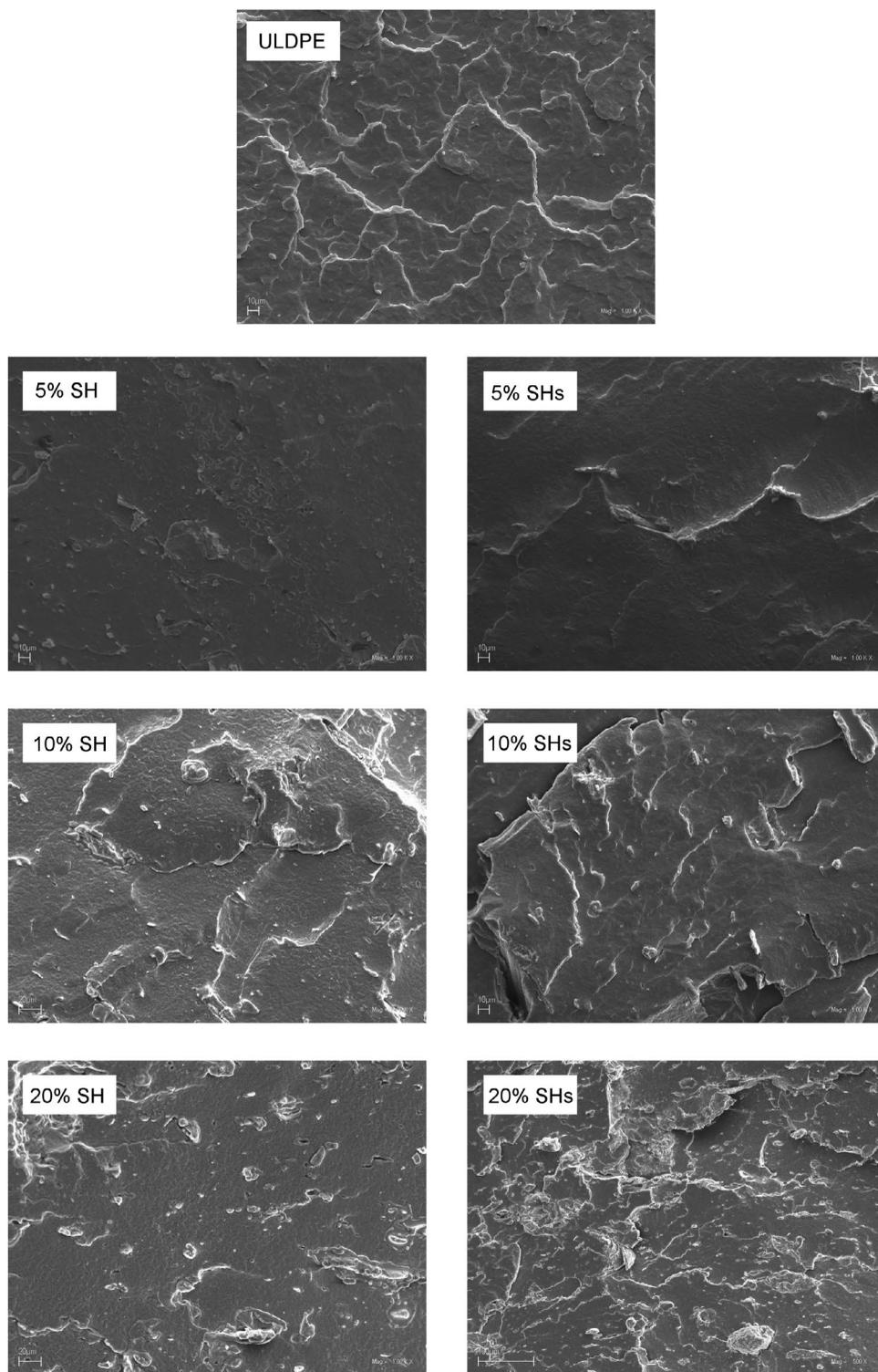


Figure 7. SEM microphotographs of ULDPPE and ULDPPE composites, magnification  $\times 500$ .

## Conclusions

The incorporation of natural fillers into ULDPE matrix allowed to obtain composites characterized by improved elastic modulus ( $E$ ) and tensile strength ( $\sigma_M$ ) with comparable elongation at break ( $\epsilon$ ). Moreover, the DMTA analysis of the mechanical properties facilitated composite behavior description at wide temperature range. It was proved that sample stiffness resulting from the addition of both fillers increased. The outcome of  $\tan\delta$ , analyzed as a function of the temperature and frequency, and rebound resilience ( $R$ ) comparison led to describing new composites as materials appropriate for mechanical vibrations and damping with a potential high impact resistance. SEM microphotographs analysis demonstrated a better dispersion of the chemically treated natural fillers in polymeric matrix and better adhesion between ULDPE and SH.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## References

- [1] Gołębiowski J, Gibas E, Malinowski R. Selected biodegradable polymers – preparation, properties, applications. *Polimery-W.* 2008;53:799–807.
- [2] Zajchowski S, Ryszkowska J. Wood-polymer composites – general characteristics and their preparation from waste materials. *Polimery-W.* 2009;54:754–762.
- [3] Ashori A, Nourbakhsh A. Bio-based composites from waste agricultural residues. *Waste Manage.* 2010;30:680–684.
- [4] Lewandowski K, Piszczek K, Zajchowski S, et al. Rheological properties of wood polymer composites at high shear rates. *Polym. Testing.* 2016;51:58–62.
- [5] Andrzejewski J, Tutak N, Szostak M. Polypropylene composites obtained from self-reinforced hybrid fiber system. *J Appl Polym Sci.* 2016;133:43283.
- [6] Jaskiewicz A, Bledzki AK, Franciszczak P. Improving the mechanical performance of PLA composites with natural, man-made cellulose and glass fibers – a comparison to PP counterparts. *Polimery-W.* 2013;58:435–442.
- [7] Joshi SV, Drzal LT, Mohanty AK, et al. Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Compos Part A Appl Sci Manufac.* 2004;35:371–376.
- [8] Bledzki AK, Reihmane S, Gassan J. Properties and modification methods for vegetable fibers for natural fiber composites. *J Appl Polym Sci.* 1996;59:1329–1336.
- [9] Saheb D, Jog JP. Natural fiber polymer composites: a review. *Adv Polym Technol.* 1999;18:351–363.
- [10] Pickering KL, Efendy MG, Le TM. A review of recent developments in natural fibre composites and their mechanical performance. *Compos Part A Appl Sci Manufac.* 2016;83:98–112.
- [11] Chun KS, Husseinsyah S, Osman H. Mechanical and thermal properties of coconut shell powder filled polylactic acid biocomposites: effects of the filler content and silane coupling agent. *J Polym Res.* 2012;19:9859. doi:10.1007/s10965-012-9859-8
- [12] Pothan LA, George CN, Jacob M, et al. Effect of chemical modification on the mechanical and electrical properties of banana fiber polyester composites. *J Compos Mater.* 2007;41:2371–2386.

- [13] Hashim MY, Roslan MN, Amin AM, et al. Mercerization treatment parameter effect on natural fiber reinforced polymer matrix composite: a brief review. *Int J Innov Res Sci Eng Technol.* **2012**;6:778–784.
- [14] Zhou X, Yu Y, Lin Q, et al. Effects of maleic anhydride-grafted polypropylene (MAPP) on the physico-mechanical properties and rheological behavior of bamboo powder-polypropylene foamed composites. *BioResources.* **2013**;8:6263–6279.
- [15] Xie Y, Hill CAS, Xiao Z, et al. Silane coupling agents used for natural fiber/polymer composites: a review. *Compos Part A Appl Sci Manufac.* **2010**;41:806–819.
- [16] Clark HA, Plueddemann EP. Bonding of silane coupling agents in Glass reinforced plastics. *Mod Plast.* **1963**;40:133–196.
- [17] Park JM, Subramanian RV, Bayoumi AE. Interfacial shear strength and durability improvement by silanes in single-filament composite specimens of basalt fiber in brittle phenolic and isocyanate resins. *J Adhes Sci Technol.* **1994**;8:133–150.
- [18] Favis BD, Blanchard LP, Leonard J, et al. The interaction of a cationic silane coupling agent with mica. *J Appl Polym Sci.* **2003**;28:1235–1244.
- [19] Koohestani B, Ganetri I, Yilmaz E. Effects of silane modified minerals on mechanical, microstructural, thermal, and rheological properties of wood plastic composites. *Compos Part B Eng.* **2017**;111:103–111.
- [20] Shaniba V, Sreejith MP, Aparna KB, et al. Mechanical and thermal behavior of styrene butadiene rubber composites reinforced with silane-treated peanut shell powder. *Polym Bull.* **2017**;74:3977–3994. doi:10.1007/s00289-017-1931-4.
- [21] Ishak ZA, Aminullah A, Ismail H, et al. Effect of silane-based coupling agents and acrylic acid based compatibilizers on mechanical properties of oil palm empty fruit bunch filled high-density polyethylene composites. *J Appl Polym Sci.* **1998**;68:2189–2203.
- [22] Maziad NA, EL-Nashar DE, Sadek EM. The effects of a silane coupling agent on properties of rice husk-filled maleic acid anhydride compatibilized natural rubber/low-density polyethylene blend. *J Mater Sci.* **2009**;44:2665–2673.
- [23] Jayamol G, Bhagawan SS, Sabu T. Improved interactions in chemically modified pineapple leaf fiber reinforced polyethylene composites. *Compos Interface.* **1997**;5:201–223.
- [24] Deepthi MV, Sharma M, Sailaja RRN, et al. Mechanical and thermal characteristics of high density polyethylene–fly ash cenospheres composites. *Mater Design.* **2010**;31:2051–2060.
- [25] Chand N, Sharma P, Fahim M. Correlation of mechanical and tribological properties of organosilane modified cenosphere filled high density polyethylene. *Mat Sci Eng A Struct.* **2010**;527:5873–5878.
- [26] Carbonell-Verdú A, García-García D, Jordá A, et al. Development of slate fiber reinforced high density polyethylene composites for injection molding. *Compos Part B Eng.* **2015**;69:460–466.
- [27] Bengtsson M, Gatenholm P, Oksman K. The effect of crosslinking on the properties of polyethylene/wood flour composites. *Compos Sci Technol.* **2005**;65:1468–1479.
- [28] Abdelmouleh M, Boufi S, Belgacem MN, et al. Short natural-fibre reinforced polyethylene and natural rubber composites: effect of silane coupling agents and fibres loading. *Compos Sci Technol.* **2007**;67:1627–1639.
- [29] Kakroodi AR, Kazemi Y, Cloutier A, et al. Mechanical performance of polyethylene (PE)-based biocomposites. In: Misra M, Pandey J, Mohanty A, editors. *Biocomposites: design and mechanical performance.* Elsevier; 2015. p. 237–256.
- [30] Sałasińska K, Ryszkowska J. Dimensional stability, physical, mechanical and thermal properties of high density polyethylene with peanut hulls composites. *Polimery.* **2013**;58:461–466.
- [31] Sałasińska K, Ryszkowska J. Composites of polylactic acid reinforced with plant fillers obtained from farm and food industry. *Przem Chem.* **2013**;92:2027–2031.
- [32] Sałasińska K, Ryszkowska J. The effect of filler chemical constitution and morphological properties on the mechanical properties of natural fiber composites. *Compos Interface.* **2015**;22:39–50.
- [33] Sałasińska K, Polka M, Gloc M, et al. Natural fiber composites: the effect of the kind and content of filler on the dimensional and fire stability of polyolefin-based composites. *Polimery-W.* **2016**;61:255–265.

- [34] Kaymakci A, Ayrimis N, Gulec T. Surface properties and hardness of polypropylene composites filled with sunflower stalk flour. *BioResources*. 2013;8:592–602.
- [35] Nerenz BA, Fuqua MA, Chevali VS, et al. Processing and characterization of a polypropylene biocomposite compounded with maleated and acrylated compatibilizers. *Int J Polym Sci*. 2012;472078.
- [36] Binici H, Eken M, Dolaz M, et al. An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. *Constr Build Mater*. 2014;51:24–33.
- [37] Howarter JA, Youngblood JP. Optimization of silica silanization by 3-aminopropyltriethoxysilane. *Langmuir*. 2006;22:11142–11147.
- [38] Datta J, Włoch M. Morphology and properties of recycled polyethylene/ground tyre rubber/thermoplastic poly(ester-urethane) blends. *Macromol. Res*. 2015;23:1117–1125.
- [39] Kardos J. The role of the interface in polymer composite – some myths, mechanisms and modifications. In: Ishida H, Kumar G, editors. *Molecular characterization of composite interfaces*. New York (NY): Plenum; 1983. p. 1–12.
- [40] Khanna YP, Turi EA, Taylor TJ. Dynamic mechanical relaxations in polyethylene. *Macromolecules*. 1985;18:1302–1309.
- [41] Liu W, Misra M, Askeland P, et al. ‘Green’ composites from soy based plastic and pineapple leaf fiber: fabrication and properties evaluation. *Polymer*. 2005;46:2710–2721.

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