



Characterization of wood plastic composites manufactured from recycled plastic blends



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ABSTRACT

The possibility of using recycled plastic waste for the manufacturing of wood-plastic composites is investigated. The samples were processed from the “light” fraction of construction plastic waste and municipal mixed plastic waste, and tested for flexural, tensile, and un-notched impact strength, hardness properties and water absorption. Thermal analysis was performed by differential scan calorimetry and thermogravimetric analysis methods; scan electron microscopy was used for morphology study of the composites. It was found that the strength of the composites was poorer than those of the reference manufactured from virgin low density polyethylene; the hardness was comparable and stiffness higher than those of the reference. The wettability of the reference was the lowest of the studied composites.

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1. Introduction

Construction and demolition waste (CDW) is one of the heaviest and most voluminous waste streams generated in the EU [1]. This waste consists of various materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, and others, many of which can be recycled. According to the EU strategy, a minimum of 70% of non-hazardous CDW must be prepared for re-use or recycling by 2020 [2]. More effective waste management, particularly increasing the recycling rate, can reduce greenhouse gas emissions, save raw materials and energy, as well as create new economic activities and jobs [3]. Thus, the EU community has strong needs and motivation to prevent waste disposal to landfill and to look for new recycling projects and technologies. The opportunities of using CDWs as aggregates in concrete [4] and fillers in wood plastic composites [5,6] have been studied.

According to statistics, the biggest plastic waste outlets in Europe, e.g. in the UK, are commercial and household packaging, approx. 58% of total plastic waste, followed by the building and construction sector, approx. 10% [7]. Construction plastic waste can contain packaging as well as non-packaging material, i.e. insulations, pipes, ducts and others. In the European Union, of the 25 Mt of plastic waste generated in 2008, 12.1 Mt (48.7%) was landfilled, while 12.8 Mt (51.3%) went to recovery, and only

5.3 Mt (21.3%) was recycled [2]. The main obstacle for more effective recycling of post-consumer plastic waste is its heterogeneity. In the plastic waste stream, low-density polyethylene (LDPE) and linear low-density polyethylene (HDPE), polypropylene (PP), polystyrene, polyvinyl chloride (PVC), polyethylene terephthalate, as well as other types of plastics [8]. The main application for recycling post-consumer plastic waste is using it as an aggregate in building materials, i.e. concrete and road constructions [9–14] and composites containing natural fibers [15–20]. In some applications, the heterogeneity of plastic waste is not significant, e.g. as filler in road construction [9]. On the other hand, the incompatibility of plastics can be the reason for deteriorated composite properties [16–20].

The developed separation methods for mixed plastic waste are usually based on the difference in the physical and chemical properties of plastics, and include spectral, electrostatic, optic, gravimetric and other techniques. However, all the applied methods have limitations, and complete separation of plastics is very difficult to achieve [21,22]. In addition, some materials are combinations of two or more types of polymer (e.g. toothbrushes, plastic bottles and their cups, etc.), which are difficult or impossible to separate [23]. Partial separation represents a more optimal way for plastic waste recycling. For example, the separation of plastic bottles and containers allowed reaching their recycling up to 57% in Europe in 2014 and their recycling rate is growing by a few percent every year [24]. The maximal rate of recycling of plastic

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bottles is 81% in Switzerland [25]. Another potential group for recycling could be PE and PP, which are the largest fraction in the plastic waste stream. Simultaneous extraction of polyethylene and polypropylene from the waste stream, e.g. by sink-float separation in water, is cost effective and not very challenging. PE and PP denoted as a “light” fraction due to the fact that their densities are lower than that of water, while a “heavy” fraction consists of polymers having densities higher than water, e.g. PVC, PS, PET, thermosets and contaminants [26]. It can be taken into account that the “light” fraction can also contain expanded polystyrene, the density of which is smaller than that of water as well. Attempts to characterize the “light” fraction has been done previously [8,17,19,27,28]. Like many other plastic pairs, PP and PE are thermodynamically immiscible, and in order to facilitate their dispersion in the blend, a third component, a compatibilizer, is loaded. The molecule of the compatibilizer is usually a block or grafted copolymer, formed from the monomers making up the mixture. The copolymer is thus miscible in the two phases, creating bonds between two completely immiscible polymers [29]. There are few papers concerning recycled PE/PP blend where reported that a small amount of suitable polyethylene/polypropylene copolymer(s) is capable to improve the properties of the PE/PP blend, particularly impact strength [19,30–33] and elongation at break [19,31,32]. In addition to the compatibilizer, different reinforcing fillers can be used to enhance of the blend performance [8,16,17,27,34]. Tzankova Dintcheva et al. have shown that the loading of fillers, namely wood fibers, glass fibers and CaCO₃, lead to a remarkably improved elastic modulus of the “light” fraction composite, whereas the impact strength and elongation at break decrease and the tensile strength remains almost unchanged [17,27]. Selke and Wichman report that wood particle incorporation could tolerate contamination of HDPE with PP, allowing the tensile strength of the composite to stay almost unchanged with the HDPE/PP ratio change [8]. On the other hand, the tensile strength of LDPE/PP composite increased monotonically with the increasing of the PP content. It should be noted that along with incompatibility there are other factors, such as changes in the morphology, aging, and impurities that can have a negative role in the recyclability of plastics.

In our previous work, we studied the processability of construction plastic waste, mostly the “light” fraction, and mixed plastic waste (MPW) available in local landfills [35]. We found that the tensile properties of plastic blends molded from recycled materials were higher than those of commercial LDPE. In the present study, recycled plastic blends are used as a matrix for the manufacturing of natural fiber composites. The composites are analyzed on a wide range of mechanical properties (flexural, tensile, impact and hardness), and their wettability. In addition, the thermal properties are studied with differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) techniques. Scan electron microscopy (SEM) is used for monitoring composite morphology.

2. Materials and methods

2.1. Sources of materials

Composites PB_C1 – PB_C9 were produced from construction plastic waste. The material was manually sorted so that only PE and PP were taken from the waste stream. The material consisted of packaging and non-packaging plastics. PB_C7 and PB_C9 were sorted additionally so that PB_C9 contained mostly flexible packaging material, whereas PB_C7 consisted of hard non-packaging material, e.g. pipes and furniture. PB_C10 was produced from municipal mixed plastic waste. The steps of plastic recycling and composite manufacturing are shown in Fig. 1. Low density polyethylene

(LDPE)-based WPC was used as reference. The polyethylene, Lupolen, density 0.91 g/cm³, melt temperature 161 °C, and melt mass-flow rate 45 g/10 min (230 °C), was supplied by INEOS Olefins & Polymers, Europe. Maleated anhydride polyethylene (MAPE), Fusabond, was used as the coupling agent. Spruce wood flour particles, on average 2.1 mm long, were produced in the laboratory. The components were loaded in the following proportions: PB/WF/MAPE/lubricant = 40/54/3/3. The ingredients were compounded by using a Weber CE 7.2 conical counter-rotating twin-screw extruder. The barrel temperatures were 160–180 °C. The melt temperature was approx. 173 °C. The pressure at the die varied between 22 and 48 bar, depending on the composite formulation, and the material output was 25 kg/h. In the case of mixed plastic blends (PB) testing, the samples were injection-molded in a Boy 30 machine. The parameters used for injection molding were the following: melting temperature 165–210 °C, injection pressure 80–91 bar, and injection time 3 s. The dashed line, Fig. 1, shows the steps of the preparation of the injection-molded samples. In the article the numbering of composite, PB_C, corresponds to numbering of PB used.

2.2. Mechanical properties

In this work, the composite samples for flexural strength, hardness and water absorption were prepared by using the original thickness of the WPC profile; the tensile and impact strength samples were cut from the bottom part of the composite material (Fig. 2). The dimensions of the samples were according to standards. The flexural and tensile properties and hardness were measured according to ISO 527-2, EN-310, EN-1534 standards on a Zwick Z020 machine. Un-notched impact strength was measured with a Zwick 5102 model impact tester in accordance with ISO 179. The tensile properties of plastic blends (PB) were tested using specimen type 1B, cut from injection-molded trial sample, according to ISO 527-2 standard test on a Zwick Z020 machine. All the physical and mechanical tests were carried out with 10–20 sample replicates.

2.3. Water absorption and thickness swelling

The water absorption (WA) and thickness swelling (TS) of the WPCs were determined according to EN 317. Water absorption and thickness swelling were calculated by the following equations:

$$WA = \frac{(m_t - m_0)}{m_0} \times 100\%$$

where m_0 and m_t are the mass of the sample before and after immersion, g.

$$TS = \frac{(T_t - T_0)}{T_0} \times 100\%$$

where T_0 and T_t are the thickness of the sample before and after immersion, mm.

2.4. Thermal analysis

Thermal analysis of LDPE and polymer blends was performed by using a differential scanning calorimeter (DSC) and thermogravimetric analysis (TGA) (Netzsch DSC 204 F1 Phoenix®). DSC was performed under nitrogen atmosphere, 40 ml/min, at heating rate of 10 °C/min. The sample, approx. 10 mg, was placed in an aluminum pan and heated from 20 to 300 °C and then cooled down to 20 °C after keeping at 300 °C for 10 min. This procedure was done twice and the thermogram of the second scan was used for the analysis. The weight loss of polymer blends was studied by TGA. The sample, approx. 10 mg, was heated from 28 to 1000 °C

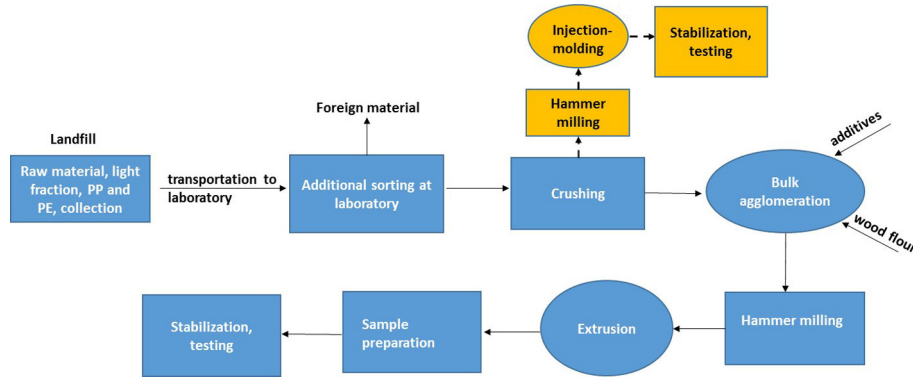


Fig. 1. Scheme for plastic blend samples and composite manufacturing.



Fig. 2. Schematic of the WPC profile.

at heating rate 10 °C/min in helium atmosphere with a purge rate of 70 ml/min. Two replicates were analyzed in each case.

2.5. Structural analysis

The fracture morphology of the composite samples was studied with a scan electron microscope (SEM), Hitachi SU3500.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Effect of wood flour on tensile properties

The effect of the wood flour (WF), 54 wt%, on the tensile properties of the composites are shown in Fig. 3. As can be seen, the samples injection-molded from polymer blends (PBs) had higher strength and stiffness compared to the sample produced from the commercial LDPE. The loading of wood flour influenced the properties of the reference sample, both tensile strength (TS) and tensile modulus (TM), positively. For the samples produced from recycled plastics, WF improved composite rigidity, increasing the

TM more than twice, but the TS decreased significantly compared to the unfilled samples. It should be said that the polymer blend samples were produced by the injection molding method whereas the WPC samples were produced by extrusion. The manufacturing method may have influenced the degree of property change [36], but nevertheless, a tendency of property change with the inclusion of the WF could be observed. The negative effect of WF on the strength can be attributed to poor compatibility between the matrix and the wood particles. Wood particles have hydrophilic nature, whereas most plastics are hydrophobic, and hence their surfaces are naturally incompatible. To avoid this problem, a coupling agent (CA) is usually applied, the molecule of which has amphipathic nature, thus showing affinity to both hydrophilic and hydrophobic surfaces. The most practical CAs are functionalized polyolefins, maleated anhydrides of polyolefins, the “head” of which has affinity to the free OH groups of wood constituents through the reactions of esterification and hydrogen bonding, whereas, the “tail” has hydrophobic affinity to the macromolecules of the polymer. CA facilitates wood particle dispersion in the matrix and improves the wood/matrix interfacial bonding. In the current case, because the matrix of most samples was PE-rich, maleated anhydride of polyethylene (MAPE) was used. Its effect on the reference sample consisting of commercial PE/WF was positive, improving TS up to 24%, but its action was not enough for the multicomponent matrix. The absence of the effect of MAPE on the PP/WF adhesion was noticeable in the PB_C7 sample. PB7 sample had the highest TS and TM values due to a dominating rigid PP fraction, about 70%. The composites produced from this material, PB_C7, had strength comparable with other samples or even less, showing 57% reduction after the WF inclusion. This property failure was similar to the composite produced from unsorted mixed plastic waste, PB_10, where the reduction was 65%. All other

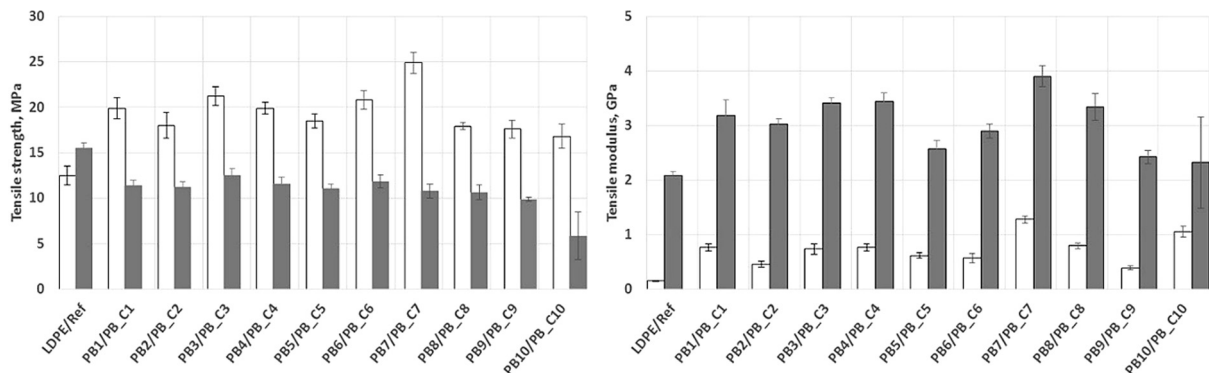


Fig. 3. Tensile properties of injection-molded virgin LDPE or plastic blends (PB) (white) and composites (PB_C) containing 54 wt% WF (dark).

samples had TS reduction between 38% and 44% after the WF loading. The loss of adhesion at the matrix/wood interface can be detected in the SEM micrographs, Fig. 4(b)–(e). In the fractures of the samples produced from secondary materials, the gaps between the matrix and wood and some voids formed after pulled-out wood particles are evidence of weak interfacial bonding. Thus, their strength or load-bearing capacity was poor due to the absence of stress transfer between the matrix and wood particles. The fracture of the reference sample had homogeneous structure, indicating compatibility between the composite constituents. It can be seen in Fig. 4(a) that the wood particle has cleaved after the fracture, thereby displaying strong bonding between the matrix and wood. Thus, the main reason for the decline of the composite properties after the WF inclusion was uncontrolled interaction between the surfaces of WF and the multicomponent matrix. The improved modulus of the composites, tensile and flexural, can be attributed to the high stiffness of wood particles and be less dependent on the interfacial bonding parameter. This is discussed in the next section.

The elongation at break, E_h , of the virgin LDPE which was used for the manufacturing of the reference, was approx. 85%. The incorporation of WF decreased its E_h to 1.7%. The elongation at break in the recycled PBs varied from 4 to 390% [35], whereas WPCs had the E_h in the 0.3–1% range (Table 1). Wood, having low elongation at break, resulted in a low E_h value of the composites. Wood particles also reduced discontinuity in the matrix, which in turn reduced its ductility and resulted in a decrease in the elongation at break. The lower E_h for the recycled composite compared to the reference was due to the incompatibility of the plastics in the blends.

3.1.2. Effect of matrix composition

Table 1 summarizes the results of the mechanical properties tests of the WPCs processed from secondary plastic blends and virgin LDPE. The results showed that the flexural strength of the composites prepared from the secondary material varied between ~10.5 and 16 MPa and the tensile strength between ~5.9 and 12.5 MPa; the reference composite showed values 19 and 15.5 MPa for the flexural and tensile strengths, respectively. Poor filler-matrix interaction leads to low strength of the composite. As it defined in the previous section, strength failure can be

explained by incompatibility/immiscibility between the matrix and the wood flour particles. On the other hand, the coupling agent used, MAPE, worked well in the reference composite with the PE matrix where the tensile strength was improved with WF loading, see Fig. 3. It was proposed that the composite properties could be dependent on the matrix content. In order to explain the results, the studied parameters were expressed as a function of the PE percentage, see Fig. 5. The concentration of PE in the matrix, shown in Table 1, was performed on the basis of FTIR calibration curves by using calibration mixtures of PE and PP [35]. For the matrix processed from municipal plastic waste, the PE content was not defined due to the PE peak overlapping with other plastics. Looking at Fig. 5(a) and (b), three tendencies for the strength behavior of the PB-composites were distinguished: samples with 50–70% PE content and samples with the highest and lowest PE amount. As can be seen, the tensile and flexural strengths for the composites with 50–70% PE increased with the increase of the PE percentage. In the figure the points of this range fit the function, the dashed lines. This tendency can probably be attributed to MAPE action. Generally, MAPE is used as a PE matrix compatibilizer, whereas for a PP matrix, a PP-based compatibilizer is used [37]. Thus, with the increase of the PE content in the PE/PP mixture, the effect of MAPE on the composite strength also increased. However, the tensile and flexural strength values for the lowest and highest PE content did not fit this conception. This was probably due to both the presence of PP and the effect of MAPE, which influenced the final result. It has been reported that the tensile strength of a LDPE/PP composite increased with the increase of the PP content significantly [8]. The composite with the minimum PP amount showed the smallest strength, where, regardless of MAPE, the strength of the composite was noticeably lower compared to the other studied composites, excluding MPW made sample, PB_C10 (Table 1). This can be explained by the fact that the plastic source for this sample was exclusively thin flexible packaging material where a large amount of LLDPE was present. Probably low synergism LLDPE with the used CA in addition to the lowest amount of PP made this composite very weak. In addition to matrix/WF low compatibility, some other factors, such as immiscibility/incompatibility of the matrix components and possible presence of heterogeneous particles influence negatively on the overall performance of the

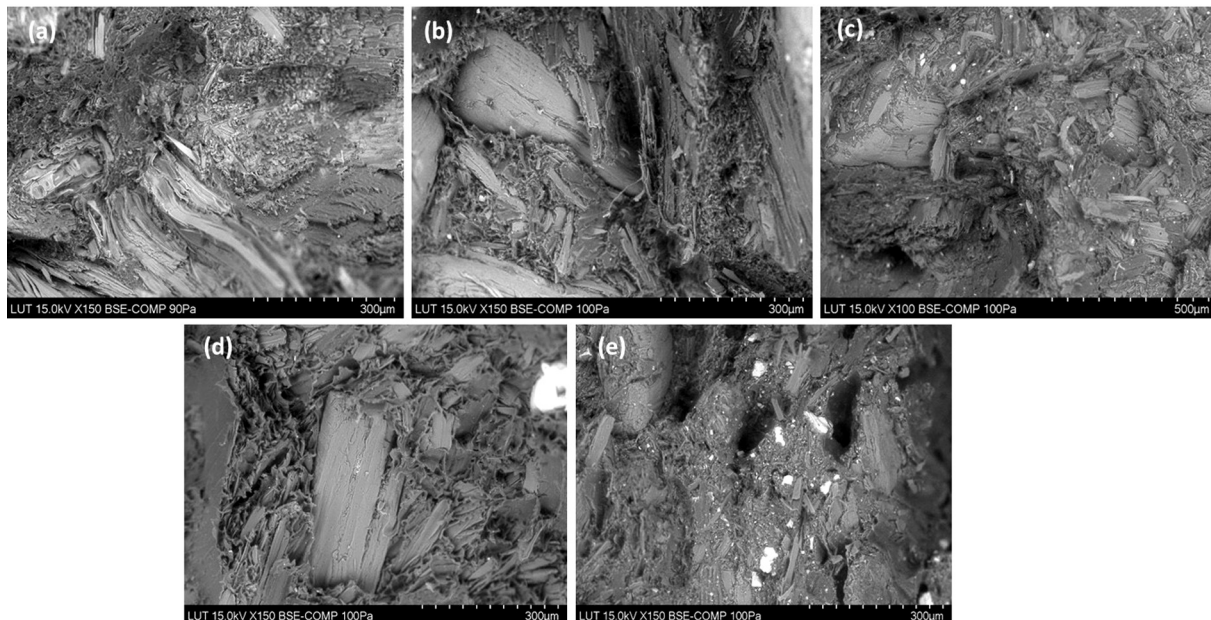


Fig. 4. SEM micrographs of the composite samples: (a) reference; (b) PB_C2; (c) PB_C5; (d) PB_C9; (e) PB_C10.

Table 1
Contents and mechanical properties of the composites. Standard deviations are shown in parentheses.

Sample	PE, [*] wt%	Flexural properties		Tensile properties		Impact strength, kJ/m ²	Hardness, N/mm ²	E _b , %
		Strength, MPa	Modulus, GPa	Strength, MPa	Modulus, GPa			
Reference	100	19.0(0.87)	1.6(0.1)	15.5(0.58)	2.08(0.08)	8.53(0.9)	4.06(0.28)	1.7(0.2)
PB_C1	53(3)	14.5(0.9)	2.64(0.23)	11.34(0.62)	3.18(0.28)	3.79(0.45)	5.05(0.48)	0.5(0.08)
PB_C2	69(3)	15.02(0.49)	2.55(0.08)	11.18(0.66)	3.02(0.1)	4.32(0.38)	4.47(0.44)	0.6(0.06)
PB_C3	72(3)	15.98(1.04)	2.94(0.16)	12.51(0.48)	3.41(0.1)	3.63(0.3)	4(0.97)	0.5(0.04)
PB_C4	69(4)	14.81(0.98)	3.0(0.25)	11.58(0.77)	3.44(0.16)	3.39(0.24)	3.73(0.52)	0.44(0.06)
PB_C5	64(6)	14.97(0.49)	2.23(0.14)	11.02(0.56)	2.57(0.15)	4.56(0.46)	4.7(0.74)	0.74(0.1)
PB_C6	62(2)	15.27(0.44)	2.7(0.19)	11.85(0.69)	2.9(0.13)	4.82(0.35)	4.4(0.44)	0.72(0.1)
PB_C7	32(2)	14.09(0.73)	3.55(0.19)	10.75(0.78)	3.9(0.19)	3.09(0.25)	4.98(1.1)	0.28(0.04)
PB_C8	52(2)	13.83(1.14)	2.75(0.29)	10.64(0.81)	3.34(0.24)	3.49(0.15)	4.64(0.58)	0.4(0.04)
PB_C9	84(4)	12.61(0.45)	1.95(0.1)	9.89(0.23)	2.42(0.12)	6.18(0.69)	3.05(0.49)	0.96(0.18)
PB_C10	-	10.45(0.56)	2.83(0.23)	5.85(2.6)	2.32(0.83)	2.94(0.26)	4.27(0.44)	0.3(0.06)

^{*} Ratio in matrix.

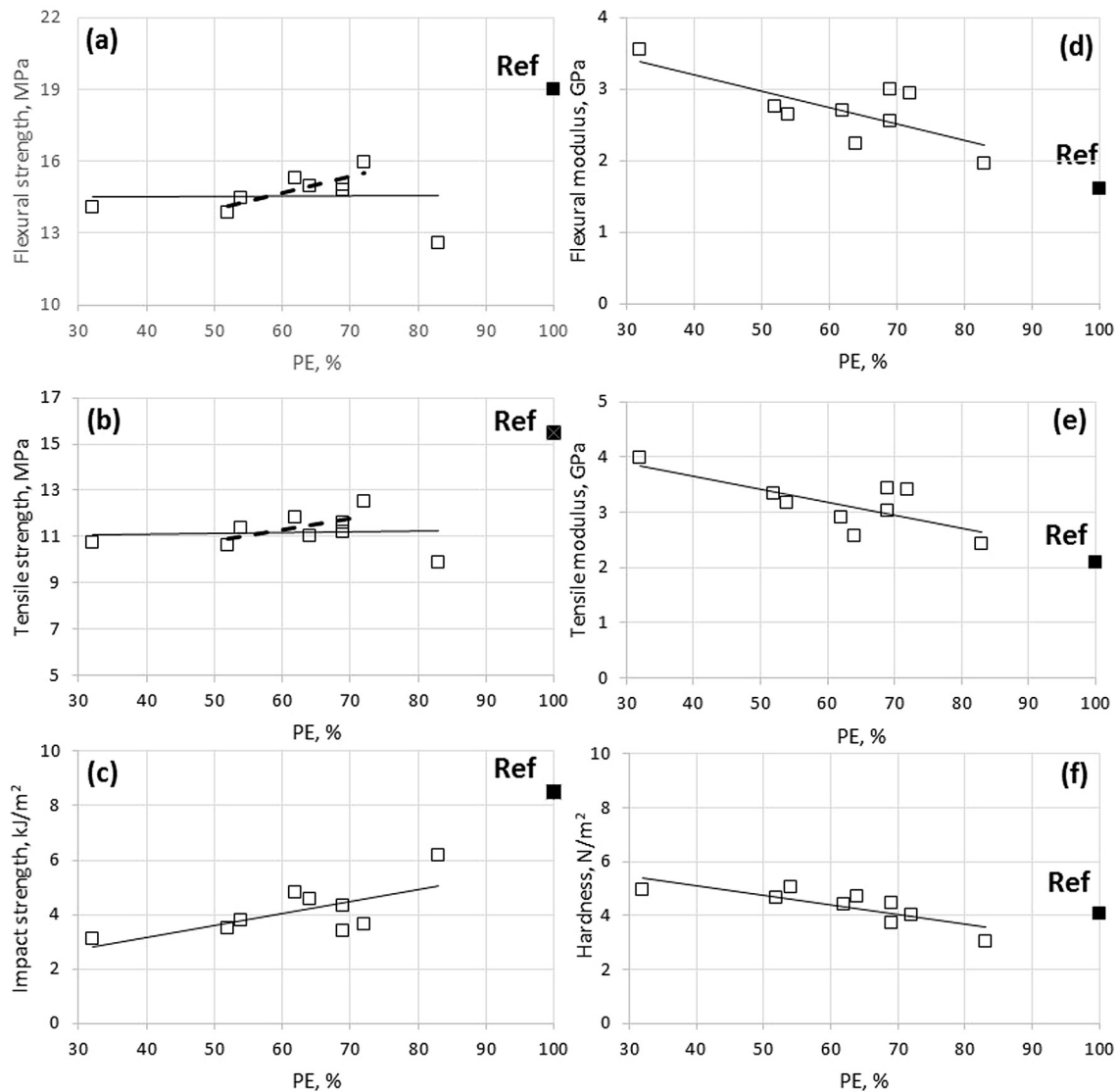


Fig. 5. Mechanical properties of the composites as a function of PE content.

composites made from the recycled plastic mixture [27]. In fact, for the stabilization of the matrix/WF interface, the coupling agent MAPE was loaded, whereas for heterogeneous matrix stabilization, no additives were applied. Kazemi et al. using both, a compatibilizer

and a coupling agent, showed improved composite properties, whereas the properties of the samples without additives declined with wood particles inclusion [33]. Additives, however, did not influence the composite modulus significantly; the modulus increased with the increased WF content (10–40%) for coupled

and non-coupled samples. In a similar work, authors studied the influence of wood fibers on the mechanical properties of the “light” fraction, and reported that the loading of 20 and 40% of wood fibers decreased the tensile strength of the composite significantly without CA or if CA was used in too large amounts, e.g. 5% [17]. Whereas 2% of a suitable CA kept the tensile strength almost unchanged. The tensile modulus of the composite increased significantly with increased wood fiber content with or without a compatibilizer, but the compatibilizer enhanced the effect of wood fibers visibly.

Unlike the strength behavior, the moduli of the composites processed from the mixed PBs were larger than those of the reference; the flexural (FM) and tensile modulus (TM) of the PB-based composites varied in the range 2–3.5 GPa and 2.3–3.4 GPa, respectively, whereas the reference moduli were 1.6 and 2.1 GPa for FM and TM, respectively. As noted above, the stiffness of wood is originally higher than that of polyolefins, and hence, WF presence enhanced the composite modulus. In addition, the modulus was higher for the composites where PP dominated, which can be explained by the higher stiffness of PP compared to PEs. Thus, unlike strength, interfacial adhesion had no significant role in the modulus. This may be explained by the fact that adhesion has no effect on stiffness at low strains, below 0.2, which was detected for our samples. According to Matuana et al. the effect of adhesion starts to be apparent at strains above 0.2 [38]. In addition, the positive effect of reprocessing, and the number of extrusions on the “light” fraction of plastic has been reported by Dintcheva et al. [27]. For example, thermomechanical stress of the polymer during reprocessing induce crosslinking and increase crystallinity, which might result in the increase of tensile properties. Dintcheva et al. also report that the TS of the polymer blend also increased, but the matrix/filler incompatibility might overcome the positive effect in our case.

The impact strength changed in the range from 3 kJ/m² to 6.2 kJ/m² depending on the matrix content, see Fig. 5(c), but was significantly lower than that of the reference, 8.5 kJ/m². The presence of PP in PE, e.g. LDPE, makes PE rigid and more fragile, leading to decrease elongation at break and impact strength (Refs. 3–5 in [19]); however due to the heterogenic nature of PEs, deviation from the mixing rule is observed. Also, the rule of mixture does not work for the LDPE and PP blend due to their immiscibility and incompatibility [19]. The addition of HDPE into PP improves the impact strength of PP, so that for a mixing ratio of 60% HDPE/40% PP, the impact strength is twice as high as for pure PP [30].

The hardness of the composites changed from about 3 N/mm² to 5 N/mm² depending on the matrix content, but was comparable with the reference hardness value, 4 N/mm² (Fig. 5(f)). The tendency of hardness decrease with the increase of PE amount can

be attributed to the greater hardness of PP than that of PE. Despite that, the hardness of the composites was comparable with the reference value, thus showing that mainly WF presence defined the hardness of the surfaces due to the fact that wood is originally harder than the plastics used.

3.2. Thermal analysis

The determination of the composition of the mixed plastic waste is important for the prediction of the end-material properties and further approaches for the control of the properties. Thermal analysis techniques, along with FTIR analysis, have become routine for the characterization of polymer mixture composition due to its simplicity and fast performance [22]. DSC analysis allows defining melting points, T_m , for an unknown polymer blend, according to which blend constituents can be distinct. DSC test results of the selected samples are shown in Fig. 6(a). The heat flow curves of the recycled plastics mixtures PB2, PB5 and PB9 show three T_m peaks, at around 114, 129 and 165 °C. Thus, based on DSC analysis it can be concluded that at least two grades of polyethylene, LLDPE and LDPE are present in the matrix. The peak at 114 °C indicates the presence of LDPE (T_m at about 110 °C) and the peak at 126 °C indicates LLDPE [39]. Usually, LLDPE is blended with LDPE to obtain packaging films [27]. HDPE can also be present in the given blends; its melting point peak, T_m at 131 °C [39], can overlap with that of LLDPE. The peak at 165 °C belongs to PP [39]. This data confirms the FTIR analysis for the studied PBs where only bands typical to PE and PP were present [35]. However, FTIR spectra showed PE spectra, overall for all kinds of PE, and hence, it was difficult to define type of PE. The sample manufactured from the municipal mixed plastics, PB10, showed additional peaks at 160 °C and 235 °C. This result is consistent with the FTIR analysis where unsigned peaks in this sample were observed [35]. In fact, household plastic waste is heterogenic, where 60–70 wt% are polyolefins and in the remaining part polystyrene (PS), polyethylene terephthalate (PET), polyvinylchloride (PVC) and traces of polyamides, polycarbonates and acrylic polymers (or others) can be found [19]. Thus, based on the DSC analysis it can be said that the matrix contained plastics with melting points exceeding the extrusion temperature, which could influence the final properties of the WPC. However, a temperature higher than 200 °C is not used in WPC manufacturing, as it can damage the wood particles. The corresponding mass loss rate curves against temperature are shown in Fig. 6(b). As can be seen, process degradation becomes noticeable only above 270–300 °C, which is significantly higher than the molding and extrusion temperatures. Less stable was sample from the municipal mixed PB, which started to degrade at about 270 °C. In the end of the experiment, about 2–8% of solid ash for the secondary materials were left. This residue may have

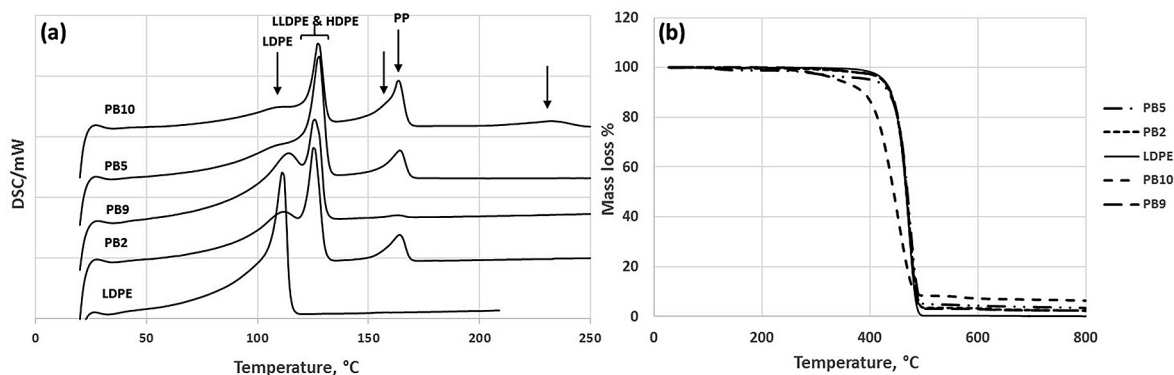


Fig. 6. Thermal analysis of the virgin LDPE and selected polymer blends used as matrix for composites: (a) DSC and (b) TGA.

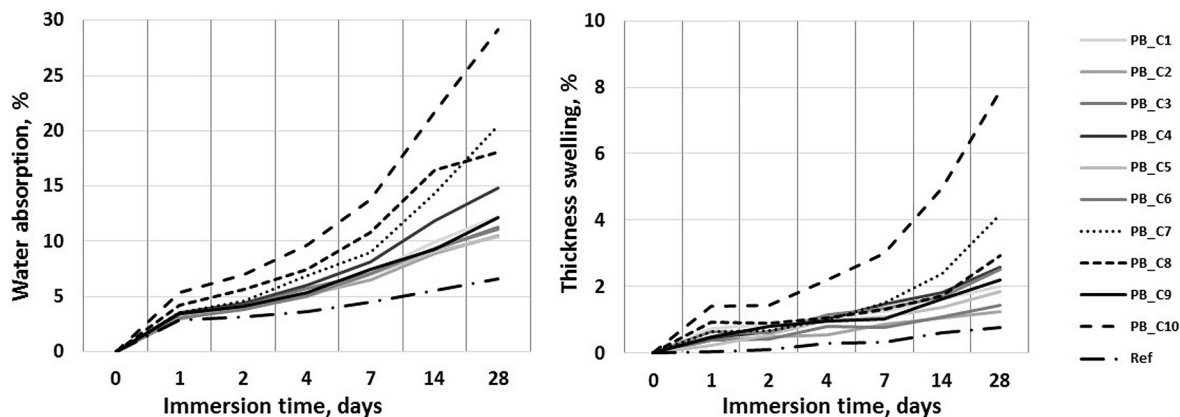


Fig. 7. Results of water absorption and thickness swelling experiments.

originated from non-polymeric contaminations in the PBs, e.g. pigments, minerals, soil, metal particles, or other fillers or impurities from landfill. SEM analysis also showed the presence of non-polymeric and non-wood particles with different sizes, up to 50 μm , see Fig. 4. The virgin PE burned completely without any amount of ash left.

3.3. Water absorption and thickness swelling

The wettability of the composites is displayed in Fig. 7. As can be seen, the immersion period, 28 days, was not enough for stabilization of the WA and TS parameters. Moreover, the amount of absorbed water and swelling started to increase faster after 7 days of immersion. The highest wettability was found for the composites made from the municipal mixed plastic waste and PB of rigid, mostly PP consisting, materials, PB_C10 and PB_C7, respectively. In addition, those composites showed low mechanical properties, which was explained by the loss of WF/matrix bonding. Poor interfacial bonding has led to gaps between wood and plastic (Fig. 4), which is easily available for water. Also, hydrophilic wood particles uncoated with plastic absorb water through hydrogen bonding between water molecules and the OH-groups on the surface of wood particles. Very probably, water damaged the interphase in those composites, which resulted in intensive water ingress and swelling of the composites after few days of immersion. The reference sample made from virgin PE had the lowest WA and TS due to strong WF/matrix bonding.

4. Conclusion

In this study, the wood plastic composite samples were manufactured from mixed plastic waste taken from different sources, construction and municipal Construction plastic waste was manually separated, so that only polypropylene (PP) and polyethylene (PE) were recycled. The samples were tested for their mechanical properties, and thermal and water absorption analysis. Based on the performed analyses, the results of this work can be described as follows:

- The strength of composites manufactured from secondary material was very poor due to incompatibility between the WF/PB phases. In the multicomponent matrix (PP/PE), the presence of the functionalized PE could partly overcome this problem but for more effective action, functionalized PP might be loaded;
- PP presence might reinforce the PP/PE blend and WPC strength overall due to the naturally stronger (strength and modulus) properties of PP.

- It was shown that wood fibers were very effective in the improvement of composite modulus, and the stiffness of the composites from secondary material was significantly higher compared to the reference; the hardness was comparable with the reference.
- Thermal analysis showed the presence of PP and different grades of PE in the construction plastic waste, whereas unsorted municipal plastic waste contained other plastics, the melting point of which was significantly higher than the temperature of the extrusion; it was found that inorganic contaminants in the amount of 2–8% were present in the recycled plastic blends.
- SEM analysis showed loss of bonding between wood particles and matrix and the presence of non-plastic and non-wood inclusions.
- The wettability of the composites depended on interfacial bonding and was the highest for the composites with poor interfacial interaction.
- The composites were processed from the secondary material with minimum pretreatment. Additional handling might lead to the improved performance of the material and an increase in the costs as well. A balance between the properties and costs could be found with further study.

References

- [1] EU waste policy – the history behind the strategy. European Commission Publication; 2005.
- [2] Green paper On a European Strategy on Plastic Waste in the Environment, European Commission, Brussel, 7.3.2013, COM(2013) 123 final.
- [3] Directive 2008/98/EC of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives. L312/3.
- [4] Kou S-C, Poon C-S, Etxeberria M. Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. *Cem Concr Compos* 2011;33:286–91.
- [5] Väntsi O, Kärki T. Utilization of recycled mineral wood as filler in wood-polypropylene composites. *Constr Build Mater* 2014;55:220–6.
- [6] Keskiisaari A, Butylina S, Kärki T. Use of construction and demolition wastes as mineral fillers in hybrid wood-polymer composites. *J Appl Polym Sci* 2016;133(19):1–7.
- [7] Hopewell J, Dvorak R, Kosior E. Plastics recycling: challenges and opportunities. *Philos Trans R Soc B* 2009;364:2115–26.
- [8] Selke SE, Wichman I. Wood fiber/polypropylene composites. *Compos Part A* 2004;35(3):321–6.
- [9] Rebeiz KS, Craft AP. Plastic waste management in construction: technological and institutional issues. *Resour Conserv Recycl* 1995;15:245–57.
- [10] Naik TR, Singh SS, Huber CO, Brodersen BS. Use of post-consumer waste plastics in cement-based composites. *Cem Concr Res* 1996;26(10):1489–92.
- [11] Marzouk OY, Dheilily RM, Queneudec M. Valorization of post-consumer waste plastic in cementitious concrete composites. *Waste Manage* 2007;27(2):310–8.
- [12] Hınıshoglu S, Agar E. Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. *Mater Lett* 2004;58:267–71.

- [13] Ismail ZZ, Al-Hashimi EA. Use of waste plastic in concrete mixture as aggregate replacement. *Waste Manage* 2008;28(11):2041–7.
- [14] Huang Y, Bird RN, Heidrich O. A review of the use of recycled solid waste materials in asphalt pavements. *Resour Conver Recycl* 2007;52:58–73.
- [15] Kazemi-Najafi S, Hamidinia E, Tajvidi M. Mechanical properties of composites from sawdust and recycled plastics. *J Appl Polym Sci* 2006;100:3641–5.
- [16] Ha CS, Park HD, Cho WJ. Recycling of commingled plastics by cellulosic reinforcement. *J Appl Polym Sci* 1999;74:1531–8.
- [17] Tzankova Dintcheva N, La Mantia FP. Recycling of the “light fraction” from municipal post-consumer plastics: effect of adding wood fibers. *Polym Adv Technol* 1999;10:607–14.
- [18] Adhikary KB, Pang S, Staiger MP. Dimensional stability and mechanical behavior of wood-plastic composites based on recycled and virgin high-density polyethylene (HDPE). *Composites B* 2008;39:807–15.
- [19] Bertin S, Robin J-J. Study and characterization of virgin and recycled LDPE/PP blends. *Eur Polym J* 2002;38:2255–64.
- [20] Fortelný I, Michálková D, Kruliš Z. An efficient method of materials recycling of municipal plastic waste. *Polym Degrad Stab* 2004;85:975–9.
- [21] Shent H, Pugh RJ, Forssberg E. A review of plastics waste recycling and the flotation of plastics. *Resour Conver Recycl* 1999;25:85–109.
- [22] Vilaplana F, Karlsson S. Quality concepts for the improved use of recycled polymeric materials: a review. *Macromol Mater Eng* 2008;293:274–97.
- [23] Ashton EG, Kindlein W, Demori R, Cândido LHA, Mauler R. Recycling polymeric multi-material products through micronization. *J Clean Prod* 2016;116:268–78.
- [24] <www.letsrecycle.com>.
- [25] <www.euro-plasticrecycling.org>.
- [26] Akovali G, Bernardo C, Leidner J, Utracki LA, Xanthos M. *Frontiers in the science and technology of polymer recycling*. Springer-Science + Business Media; 1998. p. 154.
- [27] Tzankova Dintcheva N, La Mantia FP, Trotta F, Luda MP, Camino G, Paci M, et al. Effect of filler type and processing apparatus on the properties of the recycled “light fraction” from municipal post-consumer plastics. *Polym Adv Technol* 2001;12:552–60.
- [28] Bajracharya RM, Manalo AC, Karunasena W, Lau K-T. Characterization of recycled mixed plastic solid wastes: coupon and full-scale investigation. *Waste Manage* 2016;48:72–80.
- [29] Mantia FP. *Recycling of PVC and mixed plastic waste*. Italy: University of Palermo; 1996. p. 117–118.
- [30] Schürmann BL, Niebergall U, Severin N, Burger Ch, Stocker W, Rabe JP. Polyethylene (PEHD)/polypropylene (iPP) blends: mechanical properties, structure and morphology. *Polymer* 1998;39:5283–91.
- [31] Penava NV, Rek V, Houra IF. Effect of EPDM as a compatibilizer on mechanical properties and morphology of PP/LDPE blends. *J Elastomers Plast* 2013;45(4):391–403.
- [32] Radonjić G, Gubeljak. The use of ethylene/propylene copolymers as compatibilizers for recycled polyolefin blends. *Macromol Mater Eng* 2002;287:122–32.
- [33] Kazemi Y, Cloutier A, Rodrigue D. Mechanical and morphological properties of wood plastic composites based on municipal plastic waste. *Polym Compos* 2013;34(4):487–93.
- [34] Putra HD, Ngothai Y, Ozbakkalogu T, Seracino R. Mineral filler reinforcement for commingled recycled-plastic materials. *J Appl Polym Sci* 2009;112:3470–81.
- [35] Turku I, Kärki T, Rinne K, Puurtinen K. Characterization of plastic blends made from mixed plastics waste of different sources. *Waste Manage Res J* 2016. doi: <http://dx.doi.org/10.1177/0734242X16678066>.
- [36] Stark NM, Matuana LM, Clemons CM. Effect of processing method on the surface and weathering characteristics of wood-flour/HDPE composites. *J Appl Polym Sci* 2004;93:1021–30.
- [37] Kneer TJ, Stuart RK, Brown TK. Maleated coupling agents for natural fibre composites. *Composites A* 2004;35:357–62.
- [38] Matuana LM, Park CB, Balatinecz JJ. The effect of low levels of plasticizer on the rheological and mechanical properties of polyvinyl chloride/newsprint-fiber composites. *J Vinyl Add Technol* 1997;3:265–73.
- [39] Goodship V. *Introduction to plastic recycling*. UK: Smithers Rapra Technology Limited; 2007.