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Wood–plastic composites as potential applications of recycled plastics of electronic waste and recycled particleboard

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ABSTRACT

Wood–plastic composites were injection-molded from recycled acrylonitrile–butadiene–styrene and polystyrene from post-consumer electronics in the interest of resource efficiency and ecological product design. The wood content was raised in two steps from 0% to 30% and 60%. Reinforcement performance of recycled particleboard was compared to virgin Norway spruce. Styrene maleic anhydride copolymer was used as the coupling agent in the composites with a 60% wood proportion to investigate the influence on interfacial adhesion. The composites were characterized by using physical and mechanical standard testing methods. Results showed increased stiffness (flexural and tensile modulus of elasticity), water uptake and density with the incorporation of wood particles to the plastic matrices. Interestingly, strength (flexural and tensile) increased as well. Wood particles from Norway spruce exhibited reinforcement in terms of strength and stiffness. The same results were achieved with particleboard particles in terms of stiffness, but the strength of the composites was negatively affected. The coupling agent affected the strength properties beneficially, which was not observed for the stiffness of the composites. The presence of cadmium, chromium, copper, arsenic and lead in the recycled resources was found by an elementary analysis. This can be linked to color pigments in recycled plastics and insufficient separation processes of recycled wood particles for particleboard production.

1. Introduction

Uncontrolled recycling activities of waste of electrical and electronic equipment (WEEE) cause severe impacts to human health and the environment. Open sky incineration, cyanide leaching and simple smelters to recover precious metals as well as landfilling the residues are common practices in underdeveloped, emerging, and some developed countries. The uncontrolled release of toxic substances including heavy metals, polycyclic aromatic hydrocarbons (PHAs), polybrominated diphenyl ethers (PBDEs) and many other hazardous molecules through crude recycling methods, cause severe impacts at the local, regional and global levels (Kiddee et al., 2013; Premalatha et al., 2014).

The European Union (EU-25) generates about 8.9×10^6 t of WEEE each year. Of that, 66% are domestically recovered within the EU and 18% (1.8×10^6 t) are exported outside the EU. A significant amount of WEEE is therefore recycled under the aforementioned undesirable conditions. In addition, valuable resources are lost through export – often illegal – accounting to a loss of 1.7×10^9 EUR/yr. within the EU (Huisman et al., 2015). Revenues from recycling WEEE-plastics constitute about 9% of the total revenues resulting from WEEE recycling (Cucchiella et al., 2015). Of these plastics, about 50% of the mass consist of acrylonitrile–butadiene–styrene (ABS) and polystyrene (PS) (Köhnlechner, 2014; Premalatha et al., 2014; Zoeteman et al., 2010).

It is estimated that 1.5×10^6 t of recycled ABS and PS from WEEE will be available as secondary resources in the year 2019 (Köhnlechner, 2014), as the compulsory collection rate of the European Directive 2012/19/EU on WEEE (European Commission, 2012a) shall increase to 65%. In addition, Salhofer et al. (in press) stated that in future exports will be only possible in compliance with the European Waste Shipment Regulation. However, recycling

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is only efficient and useful if a market exists for the recycled resources in accordance with the European Waste Framework Directive 2008/98/EC (European Commission, 2008).

Wood–plastic composites (WPC) are on the increase in Europe (Carus et al., 2015). On the one hand, this will result in an increasing demand for plastics derived from fossil-based hydrocarbon sources, which implies significant environmental impacts. On the other hand, a competing demand also exists for wood resources, which need to be affordable, and should be derived from sustainably managed forests (Mantau et al., 2010). In terms of resource efficiency (European Commission, 2011b) and circular economy (Haas et al., 2015), WPC tend to be a good intermediate step in the cascade chain of resources (Teuber et al., 2016).

In this study it is hypothesized that recycled ABS and PS from WEEE and recycled particleboard offer a great technical potential to apply the resource efficiency and circular approaches in innovative WPC products.

The suitability of substituting recycled crystalline thermoplastics like the polyolefins in WPC have been intensively investigated, i.e., Yam et al. (1990), Kazemi-Najafi et al. (2009), Khanjanzadeh et al. (2012), Kazemi-Najafi (2013) and Sommerhuber et al. (2015). However, research is limited concerning mechanical properties of WPC made from non-crystalline thermoplastics like ABS and PS regardless the origin of resources.

Kuo et al. (2009) showed that the tensile strength and flexural strength of virgin content ABS-WPC with 3% maleic anhydride polypropylene were lower than the pure ABS and specific tensile modulus was 40% lower. Chotirat et al. (2007) demonstrated that as the wood content was increased to a proportion of 33% in a virgin ABS matrix, the flexural and tensile modulus of elasticity (MOE) increased 50% and 63%, respectively, with decreasing flexural, tensile and impact strength. Yeh et al. (2009) compared mechanical properties of WPC made from virgin and recycled post-consumer ABS from unknown sources. The authors stressed that the recycled ABS contained various impurities, and had poor and variable mechanical properties when compared to virgin ABS. However, mechanical properties were mostly affected by the wood content. At a 50% proportion of wood flour, mechanical properties remained unchanged when the virgin ABS in the matrix is replaced by recycled ABS. Tensile modulus of the recycled ABS-WPC with 50% wood flour and 10% styrene maleic anhydride (SMA) was 12% higher than without SMA.

Pracella et al. (2010) investigated virgin PS with cellulose and oat content. PS-WPC was brittle in performance, MOE increased 32% by adding 40% cellulose and 2.5% PS-co-MA, while tensile strength and elongation at break decreased. Increasing the SMA to 5% lowered the increase in MOE to 12%. Wang et al. (2005) investigated the influence of the process factors on the physical properties of WPC panels made from three recycled-plastic packaging materials (PE, PP, and PS). The PS-WPC showed superior properties to PE and PP. The flexural strength was superior to pure PS. With an increasing of wood flour content from 30% to 50%, the specific modulus increased by 57%. Similar results were found in the study from Lisperguer et al. (2010). Lisperguer et al. (2007) studied the effect of wood acetylation on thermal behavior of PS-WPC and stated that acetylated wood flour produces WPC with better thermal stability than non-acetylated wood flour.

Chaharmahali et al. (2008) incorporated recycled particleboard in a HDPE matrix stating that mechanical properties are comparable to virgin wood particles HDPE-matrix. Likewise, Gozdecki et al. (2015) concluded the same behavior in a PP-matrix.

These short reviews support continuing research in WPC made from recycled resources. Therefore, mechanical performance of WPC made from recovered PS and ABS from post-consumer WEEE with recycled particleboard are investigated. In addition, scanning electron microscopy (SEM) evaluates the wood and polymer matrix distribution.

It has to be stated that diffusion of hazardous substances through recycling activities is prohibited by the European Waste Framework Directive 2008/98/EC (European Commission, 2008). Therefore, heavy metal content is investigated using elementary analysis to discuss potential applications.

2. Materials

2.1. Wood

The particleboard was provided by Pfleiderer AG, Germany. Both sides of the 18 mm thick particleboard were coated with a melamine overlay. The glue content (urea-formaldehyde (UF)) was determined based on nitrogen content with an elemental analyzer (vario EL cube, Elementar). UF content was calculated to be 8.5% therefore reflects the average particleboard produced in Germany, i.e., Diederichs (2014). Kiln-dried virgin Norway spruce was used for comparison.

2.2. Plastics

Recycled ABS and PS originating from WEEE, called WEplast, were provided by wersag GmbH & Co. KG, Germany. The specific monomer ratio of ABS was not known. Known properties according to the datasheets of the used recycled PS and ABS are presented in Table 1.

2.3. Additives

Styrene maleic anhydride copolymer (SMA), called SMA 3000 P, was produced by Cray Valley, France and provided by Gustav Grolman GmbH & Co. KG, Germany. SMA was used as a coupling agent to investigate its suitability in recycled ABS and PS-WPC matrices containing a 60% proportion of wood. The SMA had a molar ratio of styrene/maleic anhydride close to 3/1. The resin was provided in powder form.

The experimental design is presented in Table 2.

3. Methods

3.1. Composite preparation

Particleboard and Norway spruce were chipped with a counter blade cutter (BENZ TRONIC PLUS 3000) to a size of $20 \times 5 \times 5$ mm^3. The moisture content of the virgin wood particles was 9%, determined by the oven-drying method (103 °C/24 h). As both wood sources were stored indoors in same relative humidity over a period of >1 month, comparable moisture content for particleboard can be assumed. Particleboard and virgin wood chips were further processed separately in a laboratory grinder (Retsch SM 2000) to <1 mm mesh size. The morphology can best be described as *particles*. The specific morphology of particles was not determined further.

PS and ABS were delivered sorted as colored ‘shredder material’ with an average particle size of 6–8 mm. The plastic particles were separately extruded in a Leistritz ZSE27iMAXX-400 co-rotating, intermeshing, twin-screw extruder for homogenization purposes. The process temperature was set to 180 °C for PS and 200 °C for ABS. The screw speed for both materials was 80 rpm. The pressure was 53 bar (PS) and 60 bar (ABS). The extruded plastics were directly cut to lenses of 5 mm in diameter using a Hot Face Pelletizer (Leistritz), and air-cooled afterwards.