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UTILIZATION OF DEMOLITION WOOD AND MINERAL WOOL WASTES IN WOOD-PLASTIC COMPOSITES

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ABSTRACT
Wood and mineral wool fractions from demolished buildings were sorted into different categories and processed to the suitable grain size needed for the manufacturing of wood-plastic composites. Processed construction and demolition waste materials mixed with plastics and additives were extruded into hollow test bars using a conical rotary extruder. Test specimens needed for measurements were cut from test bars. The results showed that the mechanical performance of wood-plastic composites based on construction and demolition waste wood, and mineral wool was at a good level and comparable to commonly used wood-plastic composites in decking applications. The highest strength properties of wood-plastic composites were achieved with a plywood fraction and the lowest with materials containing a particle/fibre board fraction. The mechanical performance can be improved by utilizing mineral wool in the formulation of wood-plastic composites. A material mixture containing several wood fractions as well as mineral wool also gave good strength properties. Only a minor reduction in strength properties was measured when recycled plastic was utilized meaning that wood-plastic composites suitable for many types of applications can be produced entirely from recycled materials.

1. INTRODUCTION

Construction and demolition waste (CDW) is one of the most significant waste streams in the European Union (EU) representing a 25-30% share of all waste generation in the EU (European Commission, 2018). Recent studies concluded that EU28 countries generated approximately 351 million tons of CDW (excluding excavation materials) in 2012 (Deloitte, 2017). Especially in the Nordic countries, the proportion of CDW wood can be very high, reaching the 25-30% level (Bio by Deloitte, 2015). However, the recycling rate of CDW wood is low and the material is currently being mainly used in energy recovery purposes (Bio by Deloitte, 2015). At the moment, CDW wood is used to some extent in particle boards, ground covers and animal beddings, for example (Bio Intelligent Service, 2011). The utilization of CDW wood in the production of pulp, wood panels and biofuels was studied in DEMOWOOD project (Era-learn), and in wood-plastic composite (WPC) production in the IRCOW project (Garcia et al., 2013).

The exact volume of CDW mineral wool currently in use in the buildings stock is challenging to define due to the lack of reliable data. However, Väntsi and Kärki (2014) estimated with the model introduced by Müller et al. (2009) that the annual mass of CDW mineral wool in EU27 countries might exceed 2.5 million tons in 2019. Despite several options for mineral wool waste recycling, it is commonly disposed of at landfill, due to a lack of widely available recycling systems (Väntsi, 2015). Currently recycling opportunities for mineral wool waste are related, for example, to recycling it in mineral wool production (Holbek, 1987; European Commission, 2004) and its utilization in the production of cement-based composites (Cheng et al., 2011), hybrid particleboards (Mamiński, et al., 2011), ceiling tiles (Dunser, 2007), composite ceramics (Balkevičius and Pranckevičienė, 2008) and wood-plastic composites (Väntsi and Kärki, 2014; Väntsi, 2015). At the moment almost all mineral wool wastes will be deposited in landfills in Finland. However some companies offer recycling solution, which is based on crushing the mineral wool panels to mineral-wool loose material. Mineral wool is classified non-hazardous material, but there is a limit for long-term dust exposure and in very dustable work personal protective equipment should be used.

The Waste Framework Directive (WFD) 2008/98/EC, amended by Directive /2018, states that reuse, recycling and other material recovery of non-hazardous CDW should be increased to 70% in the EU by 2020 (European Parlia-

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ment and Council, 2008). On the other hand the Landfill Directive 1999/31/EC requires that EU countries should reduce landfilling of biodegradable municipal waste to 35% of the total amount of biodegradable municipal waste existing in 1995 by 2016 (European Parliament and Council, 1999). Tightening regulations together with environmental benefits achieved by CDW recycling will raise the need to increase the recycling rate of CDW significantly in the future. According to the amendment of the WFD, the Commission shall consider setting the recycling targets for construction and demolition waste and its material-specific fractions by 31 December 2024 (European Parliament and Council, 2008). In practice, this means that in future there might be specific recycling targets, e.g. for wood waste.

In recent years, WPCs have started rapidly gaining popularity in the construction and automotive sectors. The global markets for WPCs were approximately 2 million tons in 2014 and the volumes are growing rapidly (Chen, 2014). The three leading regions are North America, Asia and Europe and the main applications are decking and railings (Chen, 2014). CDW materials are not yet largely used in WPC-manufacturing because of the common challenges related to recycling of CDW materials like ensuring raw material purity and steady availability as well as processing and transportation cost issues (Dolan et al., 1999;Väntsi and Kärki, 2014). However if these challenges can be solved, the utilization of CDW materials in WPCs can offer many benefits for WPC producers, including improved environmental performance, improved material efficiency and even improved cost competitiveness.

The objective of this investigation was to determine the potential of CDW wood and CDW mineral wool as a raw material for WPCs. The influence of different CDW wood fractions as well as CDW glass and stone wool on the mechanical properties of WPCs was clarified. Bending and impact strength measurements were used as standard methods, to evaluate the performance of the produced WPC materials.

2. MATERIALS AND METHODS

2.1 Raw materials and processing

CDW wood and mineral wools from demolished buildings were transported to the handling terminal for pre-treatment. CDW wood was sorted by hand into four different categories according to origin and purity: clean wood fraction, painted wood fraction, plywood fraction and particle/fibre board fraction. CDW mineral wool was sorted by hand into glass and stone wool fractions. The composition of glass and stone wool is different. Glass wool is made from silica sand, limestone and soda ash or recycled glass. Stone wool is made from volcanic rock like basalt. Addition to these basic raw materials mineral wools contain additives like resin binders (European Mineral Wool Manufacturers Association, 2018). Based on the origin of rock or sand the composition of stone or glass wool can vary. The end use application effects also on the composition of mineral wool. Bigger impurities like stones, concrete pieces, metal and plastic particles as well as pressure impregnated wood include preservatives (classified to hazardous material) were also removed from CDW wooden and mineral wool fractions by hand at this stage. CDW wooden fractions were further processed with pre- and post-crusher to downsize the particle size of raw materials to a suitable size for the refining process. Pre- and post-crushing was not needed for CDW mineral wools.

Wooden materials were fed to a pre-crusher unit, supplied with an electrically driven fixed hammer mill. The technical specifications of the pre-crusher and post-crusher were as follows: The rotor speed of the pre-crusher was 1000 1/min and power 75 kW. The feeding table was 1.6 m wide and it is equipped with belt conveyor and upper feeding roller. The processing capacity was 100–250 loose m^3/h depending on fed material. The post-crusher was located in the same line as the pre-crusher and was fed with the feedstock coming from the pre-crusher by a belt conveyor. The electrically driven post-crusher was a high speed swinging blade hammer mill with a rotor speed of 1250 1/min and power of 160 kW. The processing capacity and width were the same as in the pre-crusher unit. A magnetic separator was used for removing magnetic metals from post-crushed materials.

At the pre-crushing phase, the average particle size of sorted CDW wooden fractions was decreased below 0.5x0.5 m. A post-crusher with a screen mesh size of 70 mm downsized the average particle size of CDW wooden fractions below 80 mm.

Cleaning operations of post-crushed CDW wood were continued with an air separator where non-magnetic and magnetic metal particles, gravel and sand were removed. The air separator was equipped with a vibrating feeder table, from where the material was dropped in a thin (thickness 1-3 cm) uniform layer. Magnetic separation was located at the beginning of the material free fall and after that a laminar horizontal airflow began to separate the falling material. Heavier particles like concrete, stones, metals, glass etc. fall vertically away from airflow and the lighter wood particles fly horizontally with air-flow. Separation to wood and reject (heavier particles) categories was done by adjusting the position of the separation wall located inside the air separator. The separated wood material was transported with belt conveyors to the pre-refining phase.

The hammer mill used in the pre-refining phase was equipped with swinging blade hammers and a 10 mm screen. The pre-refiner was powered by a 400 kW diesel engine. The post-refiner was a swinging blade hammer mill equipped with a 4 mm screen, powered by a 50 kW diesel engine. Two magnetic separators were located between the pre- and post-refiners and after post-refiner.

At the pre-refining phase, the particle size of CDW wooden and mineral wool fractions was downsized below 10 mm by hammer mill (screen mesh size 10 mm). The particle size of CDW wooden and mineral wool fractions was reduced to below 4 mm by hammer mill (screen mesh size 4 mm) at the post-refining phase. Finally, refined CDW wooden and mineral wool fractions were dried to dry solid content of 80-85% by waste heat coming from post-refining process.

2.2 Composite processing: raw materials, mixing, extrusion

In addition to the processed CDW wood and mineral wool fractions, the raw materials used in the production of extruded WPC test bars are presented in Table 1.

The main production phases of the fibre-plastic composites were mixing and extruding. At the mixing phase, agglomerates consisted of CDW wooden and mineral wool fractions, plastic and additives, which were formed by high-speed mixer unit. CDW wooden material, which contains 15-20% of moisture, was also dried at the mixing phase to a dry solid content above 98%. The agglomerates were extruded into 1 m long hollow test bars 60 x 40 mm in size with 8 mm wall thickness using a conical rotary Conex®-extruder type CWE 380-1.

The high-speed (batch) mixer unit consisted of two separate bowls; an upper (hot) bowl, 100 litres in size, for mixing and a lower (cold) bowl, 200 litres in size, with a water circulation jacket for cooling. The diameter of the mixing bowl was 800 mm and it was equipped with three mixing blades. The cooling bowl was equipped with one mixing blade and its diameter was 1000 mm. In these experiments the loading batch quantity was 30 kg of total mixture and the mixing speed used was 1350 rpm in the mixing bowl. During the mixing cycle of approximately 25 minutes, the temperature in the mixing bowl and the load on the mixing bowl motor were measured. Both temperature and drive load measurement data were used to monitor the agglomeration rate of the mixture and when the agglomeration was completed agglomerates were discharged into the cooling bowl. After a cooling time of approximately ten minutes, agglomerates were ready to be discharged into the container from the cooling bowl.

A Conex®-extruder CWE 380-1 consists of a rotating conical rotor with spiral groove geometry and holes for mixing the material composition fed from two sides at 3 and 9 o'clock positions via placed screw feeders. The rotor diameteris 380 mm at the feeding side and 100 mm at the tip. The rotor is surrounded on both sides from inside and outside by heated (electrical and/or oil circulation) stationary stators with "mirror shaped" groove geometry to match the rotor geometry. Each stator heating is divided into two individual sections; the feeding zone and the melting zone. In these experiments, the temperature of the feeding zone was set to 120°C and the melting zone to 160°C. The rotational speed of the rotor was 5 rpm and the flight clearance (gap) between the rotor and stators was 0.5 mm.

Overall 14 different WPC materials based on CDW wood and mineral wool fractions were extruded for further studies (Table 2).

TABLE 1: Raw materials used in the production of WPCs.

	Trade name, description	Form	Supplier
Polypropylene	BC245MO, copolymer, MFR 3.5 g/10 min *	Granules	Borealis
Recycled polypropylene	Consumer bottles, mixed colors, MFR 1 g/10 min *	Flakes	Swerec
Talc	Finntalc M30, filler	Powder	Mondo Minerals
Maleic anhydride acid (PP-g-MAH)	Licocene® PP MA 7452, coupling agent	Granules	Clariant
Blend of modified fatty acid ester	Struktol® TPW 113, processing aid	Granules	Struktol

** MFR: Melt Flow Rate*

TABLE 2: Extruded WPC materials. Numbers in the table indicate the amount of materials (percentage by weight).

	Abbr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Wood fractions															
Clean wood	W	60		63	58	63	58								63
Painted wood	PW		63						19	48	38	48	38		
Plywood	PLY								17					68	
Particle/fibre board	MDF							63	17						
Mineral wool fractions															
Stone wool	SW			5	10				5			20	30		
Glass wool	GW					5	10		5	20	30				
Plastic															
Polypropylene virgin	PP	27	25	25	25	25	25	25	25	25	25	25	25	25	
Polypropylene recycled	PPr														25
Additives															
Talc		5	5					5	5						5
Processing aid		6	5	5	5	5	5	5	5	5	5	5	5	5	5
Coupling agent		2	2	2	2	2	2	2	2	2	2	2	2	2	2

2.3 Testing

The particle sizes of CDW wooden fractions were determined according to the ISO 17827-2:2016 standard (ISO 17827-2:2016, 2016). In this method CDW wooden fractions are screened through vertically positioned and horizontally oscillating sieves with square apertures to sort wooden particles mechanically into descending size classes. The sizes of apertures of sieves from top to bottom are 16.0 mm, 8.0 mm, 4.0 mm, 2.0 mm, 1.0 mm, 0.71 mm, 0.5 mm, 0.315 mm, 0.250 mm, 0.180 mm, 0.125 mm, 0.090 mm and 0.063 mm. Total amount of analysed wooden material was 50 g per fraction. The fibre dimensions of CDW glass and stone wool were analysed by the L&W FiberMaster fibre analyser. Measured fibre quantity was approximately 5300 fibres for glass wool and 3000 fibres for stone wool.

Test specimens for flexural and impact strength measurements were cut from WPC test bars and they were kept under standard conditions (23°C, 50% relative humidity) for at least five days before testing. Flexural tests were performed according to the ISO-178 standard using an Instron 4505 Universal Tensile Tester (Instron Corp., Canton, MA, USA) with a 1 kN load cell and a 1 mm/min cross-head speed (ISO-178, 2019). Test specimen thickness was 8.5±1 mm, width 20±1.5 mm and length 200±2 mm. The impact strength was measured using a Charpy Ceast 5.5 Impact Strength Machine according to the ISO-179 standard (ISO-179, 2010). The test was performed on un-notched specimen, which thickness was 8±1 mm, width 10.5±1 mm and length 80±2 mm. Each value obtained represented the average of five samples in flexural test and the average of ten samples in impact test. Standard deviation was used to quantify the amount of variation of parallel measurements.

3. RESULTS

Particle size distributions of refined CDW wooden fractions and length distributions of refined CDW mineral wool fractions are shown in Figure 1 and Figure 2. It can be seen from Figure 1 that there is a clear difference in particle size distributions between CDW wood and building board fractions. For clean wood and painted wood fractions a particle size between 1-2 mm represented a proportion over 50% of the total mass. However, the same particle size fraction represented only about a 30% proportion for the plywood and particle/fibre board fractions. The share of particles varying between 0.3-1 mm was 30 to 35% for CDW wooden fractions and 45 to 55% for CDW building board fractions. It should be also noted that the proportion of particles smaller than 0.18 mm was clearly highest in the MDF fraction. The average particle size for clean wood, painted wood, plywood and particle/fibre board fractions were 1.10 mm, 1.14 mm, 0.85 mm and 0.90 mm respectively.

The highest amount of CDW stone and glass wool material fell into the 0.05-0.5 mm fibre length category (Figure 2). The proportion of this category was approximately 85% for the stone and 78% for the glass wool fraction. The proportion of fibres longer than 0.5 mm was higher in the glass wool material than in the stone wool material. The length weighted average fibre lengths and widths for glass wool were 0.53 mm and 14.40 μm and for stone wool 0.39 mm and 16.30 μm respectively.

The flexural and impact strength results of WPC materials containing CDW wooden fractions correlated closely to each other (Figure 3). The lowest strengths were achieved with materials containing a particle/fibre board (MDF) fraction and the highest with materials containing a plywood (PLY) fraction. It was noted that the MDF fraction included hard particles like melamine particles, which can be assumed to cause defects (weak points) in WPCs. The dust content of MDF fraction was also much higher than the other CDW wooden fractions leading to reduced reinforcement capability. The PLY fraction gave slightly better results vs. other tested materials. This could be from the influence of adhesives used in PLY manufacturing promoting

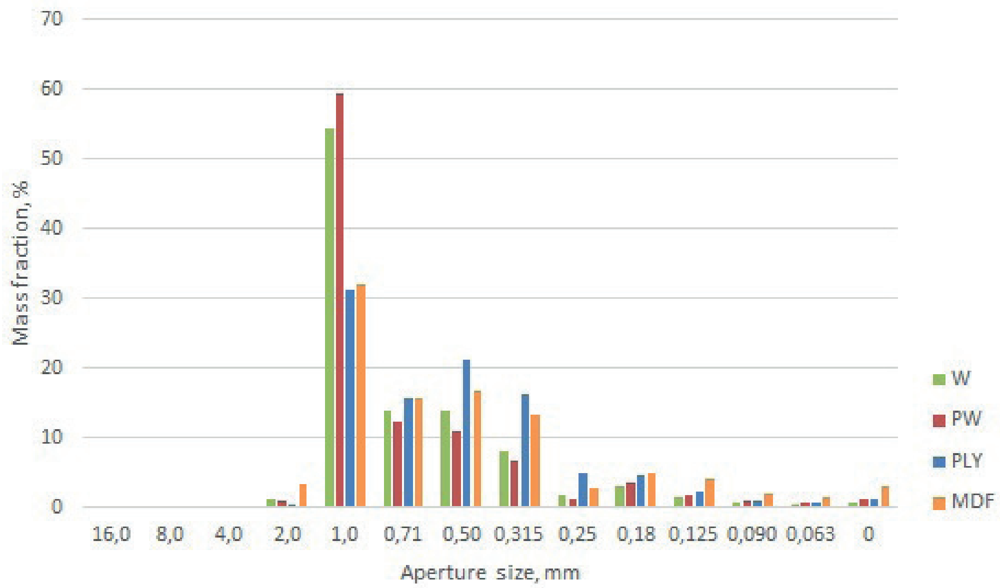

FIGURE 1: Particle size distributions of refined CDW wooden fractions: clean wood (W), painted wood (PW), plywood (PLY) and particle/fibre board (MDF).

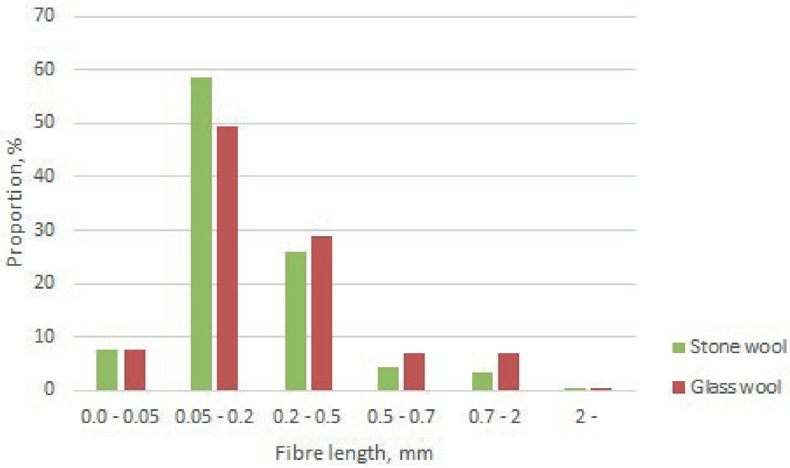

FIGURE 2: Length weighted length distributions of refined CDW glass and stone wool fractions.

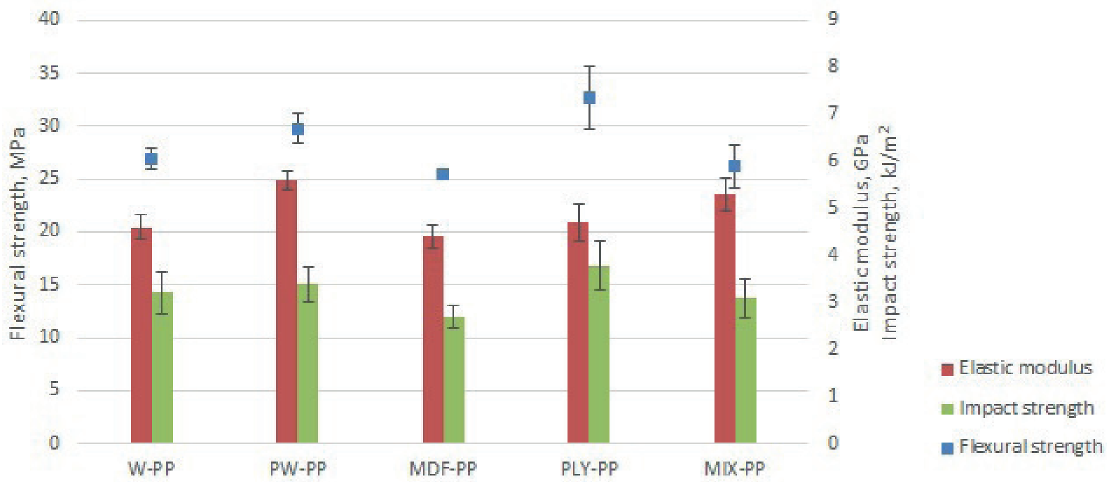

FIGURE 3: Flexural strength, impact strength and elastic modulus of WPCs based on CDW wooden materials. Error bars represent standard deviation. CDW fractions are clean wood (W), painted wood (PW), particle/fibre board (MDF), plywood (PLY) and mixed CDW material (MIX). Polymer matrix in all cases is polypropylene (PP).

improved coupling between the natural fibres and polymer matrix. Based on the flexural and impact strength results of the painted wood (PW) fraction we can conclude that there is no need to remove paints or lacquers, for example, from the surfaces of wood before WPC production. Mixed CDW material (MIX), where both mineral wool fractions and all other CDW wooden fractions except clean wood (W) fraction were used, also gave good strength results meaning that there is no need, necessarily, for CDW wood sorting before the production of WPCs and CDW mineral wools can be processed together with CDW wooden fractions in the production of WPCs.

Generally speaking, compared to commercially available products (Haider and Leßlhumer, 2015), the flexural strengths of the produced WPC materials were at a good level, above 25 MPa, and the elastic moduli of all WPCs were high, above 4 GPa (Figure 3). In fact, elastic modulus values over 5 GPa are exceptional high. The impact strength level of the produced WPC materials was quite low, which is a typical feature for high filled WPC materials.

As we can see from Figure 4 the mechanical properties of WPCs based on CDW wood can be improved by utilizing CDW mineral wools in the production of WPC materials. The results indicated that there was an optimum dosage level (near 20%) for CDW mineral wools, where the highest flexural and impact strength was achieved. However it seemed that a 30% dosage level of CDW mineral wool was already too much, leading to deterioration of mechanical properties.

The results achieved differ somewhat from the earlier findings by Väntsi et al. (2014). They concluded that the dosage of CDW stone wool had a positive effect on impact strength of WPCs, but a negative effect on flexural strength. Cui et al. reported that the effect of glass fibres on the impact strength of WPCs could be a positive or negative depending on the glass fibre type (Cui and Tao, 2008). Findings related to flexural strength are inconsistent, i.e. the addition of glass fibres can reduce (Ashrafi et al., 2011) or improve (Valente et al, 2011) the flexural strength of WPCs. One of the main factors affecting the mechanical properties of WPCs is the interfacial adhesion between the

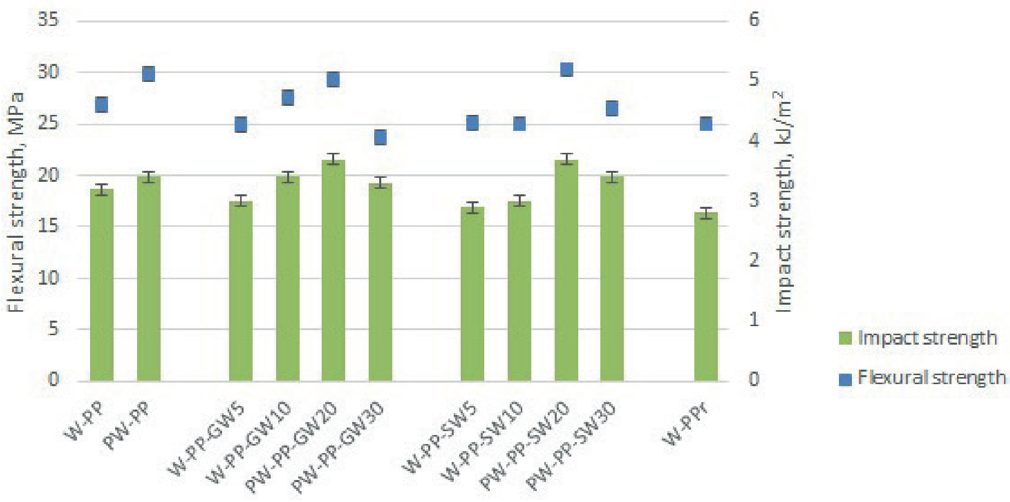

FIGURE 4: Flexural and impact strength of WPCs containing CDW glass wool (GW) or stone wool (SW). Number behind the abbreviation meaning the share of glass or stone wool. Error bars represent standard deviation. Reference materials are clean wood (W) and painted wood (PW) containing WPCs without mineral wool. Polymer matrix is virgin polypropylene (PP) or recycled (PPr) polypropylene.

filler materials and the polymer matrix (Cui and Tao, 2008; Petinakis et al., 2009; Ashrafi et al., 2011; Valente et al, 2011; Poletto et al., 2011) and this adhesion can vary, for example with the glass fibre type.

A small reduction in flexural and impact strengths of WPCs can be noticed when recycled polypropylene is utilized (Figure 4). However, for several applications a strength reduction of this magnitude is not significant, meaning that in many cases WPCs can be totally produced from recycled raw materials. Of course, it should be noted that the mechanical properties of WPCs based on the recycled plastics depend heavily on the quality of the recycled plastics (Kazemi-Najafi, 2013).

4. CONCLUSIONS

We showed that the mechanical performance of wood-plastic composites based on construction and demolition waste wood and mineral wool was at a good level and comparable to commonly used wood-plastic composites in decking applications, and therefore offers very attractive raw material alternatives for wood-plastic composite production. The highest strength properties of wood-plastic composites were achieved with a plywood fraction and the lowest with materials containing a particle/fibre board fraction. The mechanical performance can be improved by utilizing mineral wools in the production of wood-plastic composites. It seemed that the optimum dosage level of mineral wool is approximately 20%. Material mixtures containing different wood fractions as well as mineral wool also gave good strength properties meaning that there is a possibility to utilize a relatively compact processing concept without many sorting phases. It is obvious that significant cost savings at the raw material processing phase can be achieved by simplifying the processing concept. Only a minor reduction in strength properties was noticed when recycled plastic was used, offering savings to raw material costs. The results showed that wood-plastic composites could be produced totally from recycled materials thus promoting the circular economy and reducing waste in the construction and demolition sectors. In addition wood-plastic composites are recyclable i.e. all materials can be re-used or processed by plastic processes to new products.

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