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The effect of the use of construction and demolition waste on the mechanical and moisture properties of a wood-plastic composite

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Abstract

Recycling of construction and demolition waste (CDW) which contains materials with high resource value such as plastics, metals, wood, glass and concrete has been investigated in recent years due to tightening environmental legislation. Wood-plastic composites as an environmentally friendly material provide a possibility to enhance the recycling of material. The effect of the addition of CDW on the mechanical and moisture properties of WPC is studied in this paper. Three types of wood-plastic composites were manufactured with different amounts and composition of a CDW filler. Their properties were compared to the reference composite manufactured with virgin wood fibers and polypropylene as the polymer. It was found that the addition of the CDW filler weakened the mechanical properties of the composite generally, except for the fact that the Charpy impact strength was improved significantly. Minor variations in the composition of the CDW filler did not have an impact on the mechanical properties, but an increase in the amount of filler increased the deterioration of mechanical properties. For moisture properties, the addition of the CDW filler decreased the water absorption and thickness swelling of the composites. An increase in the filler content improved the thickness swelling more significantly than water absorption.

1. Introduction

Construction and demolition industry generates a large quantity of solid waste around the world, causing environmental problems due to its uncontrolled disposal [1–3]. Tightened environmental regulations and laws concerning the recycling of construction and demolition waste (CDW) have been implemented in several countries[4], which has forced the companies to improve and encourage material efficiency and the recycling of wastes. For example, according to the binding legislation set by the EU, 70% by weight of non-hazardous CDW has to be prepared for re-use, recycled, or recovered by the year 2020 [5]. In addition, the new plastic strategy of the EU outlines that all plastic packaging placed on the EU market shall be either reusable or can be recycled by the year 2030 [6].

Variation in the volume and composition of CDW causes challenges for re-use and recycling. CDW consists typically of various materials, including metals, plastics, wood, gypsum, glass, insulation, brick, concrete, and others, many of which can be recycled.

Waste materials from new construction are primarily clean and relatively uncontaminated such as unused or damaged raw materials as well as packaging materials [7], whereas demolition wastes are usually dirty or contaminated and mixed with other materials. These differences create specific challenges as well as opportunities for recycling and waste sorting technologies [7–9].

Wood-plastic composite (WPC) is an environmentally friendly material because the source of the raw material can be either virgin or recycled (non-virgin) materials. The utilization of recycled or waste materials in WPCs reduces the manufacturing costs, energy and depletion of virgin materials. If the waste or recycled materials, especially plastics, are considered as new materials in WPC manufacturing, it is necessary to understand primarily the impact of the waste or recycled materials in WPCs [10]. Generally, composite material is defined to be a multi-phase system consisted of matrix material and reinforcing phase [11]. Typically, WPCs contain polymers as matrix, wood fibers as reinforcement and some additives. Virgin thermoplastic polymers are widely used in WPC manufacturing, but the use of recycled thermoplastics has increased significantly in recent years [10]. The most prevalent polymers are low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP) and polyvinylchloride (PVC). Possible additives include for example lubricants, colorants, ultraviolet stabilizers and flame-retardants [12]. The additives are used to improve the durability of composite [13]. Due to the hydrophilic nature of bio-based fibers and the hydrophobic nature of plastics, the most important additives are coupling agents, which are used to improve the adhesion between fiber and matrix. WPCs are typically used in outdoor applications, such as decking, siding and window framing, where these material are exposed to moisture, freeze-thaw actions and ultraviolet light in sunlight. This has raised concern about their durability, including mechanical properties and moisture resistance [14].

The raw materials and additives used in WPC manufacturing, as well as the processing methods and parameters, correlate with the mechanical, physical and thermal properties of WPCs [15]. The significant advantages of polymer matrix composite materials are their high specific strength and high specific modulus [11] as well as the properties of WPC material can be tailored to meet the needs of a specific application. The thermoplastic polymer matrix has an important role in the formation of the final properties of WPC material. The matrix distribute the applied load uniformly and transfer the loads to fibers. The addition of wood fiber components tends to increase mechanical properties of WPCs, such as the stiffness, while the thermoplastic component improves their moisture resistance [16].

In outdoor applications, the weathering properties are essential for the durability of WPC. At the surface of WPC, the wood components absorb water and swell. Water absorption can lead to a degradation of mechanical properties of WPC. As known, moisture absorption and thickness swelling increase with the increase in fiber content. However, the use of coupling agent as additive reduces water absorption and thickness swelling significantly [17]. Therefore, reduced moisture absorption leads to increased durability and dimensional stability [18]. Most of the moisture and mechanical properties of WPCs depend mostly on the interaction developed between wood and the thermoplastic material. Good interaction is essential to transfer stress from the matrix to the fibers and thus improve the mechanical strength of the composites [19]. Mechanical properties and dimensional stability of composites can be achieved by the addition of coupling agent in manufacturing of WPC [17]. Some mechanical properties, such as tensile strength, impact strength, and hardness of WPCs, can be improved with the addition of mineral fillers. On the bending properties, the use of mineral fillers has a negative effect. Furthermore, improved impact strength appears as increased brittleness of WPC [12,17].

The potential of recycled wood fibers and polymers in WPCs has been widely examined in several studies that indicated recycled fibers and polymers can be used to produce WPCs with mechanical and moisture resistance properties comparable to WPCs made of virgin ones. Mechanical properties are more depending on the fiber content in the composite material than their origin. Kazemi Yasamin et al [20] found that with a fiber loading of 50 wt% composites made from mixed recycled plastics exhibited statistically higher flexural moduli compared with those of mixed virgin plastics. The study of Moreno and Saron [21] revealed that LDPE-waste/recycled wood composites with low fiber content (1.5–10%) had higher elongation and less expressive Young's modulus compared to composites with fiber content above 10% is opposite. Taufig et al [22] studied the mechanical properties of WPCs manufactured from recycled PP/PE blends reinforced with different kenaf fiber loadings. It was found that the maximum flexural strength was achieved with 30 wt% of fiber loading whereas the maximum modulus was at 60 wt% of fiber loading, whereas the addition of fiber loading was not observed to improve the impact strength of studied WPCs.

Also the effect of the use of recycled plastics in WPCs has been studied because the use of recycled thermoplastic polymers and natural fibers in WPC manufacturing has been an interesting alternative to produce polymeric materials of low cost, with sufficient properties for application and environmentally adequate [23]. Turku et al [24] studied durability of wood-recycled plastic composites and found that the influence of weathering was greater in composites made of plastic waste compared to a composite made of virgin material. After weathering, the mechanical properties, tensile and flexural, were reduced by 2–30%, depending on the plastic source. The other study of Turku et al [25] revealed that the use of recycled plastics decreased the strength of WPCs due to incompatibility between the wood flour/plastic blend phases. The research also indicated that wood fibers significantly improved composite modulus, and the stiffness of the composites manufactured from recycled plastic material was remarkably higher compared to the reference made of virgin LDPE.

As well as the utilization of specific waste streams such as construction waste and industrial waste have been the subject of many research [26–28]. As well as, several studies have revealed that combining of different fillers, such as wood fibers and mineral fillers, in composites can be useful [29–31]. Hybrid composites combining at least two different type of fillers possess different properties that cannot be obtained with a single type of filler [32]. As known, CDW provide a wide range of recyclable different materials such as fibers, polymers and mineral fillers that can be utilized in composite manufacturing. Therefore, the potential of CDW as a source of recycled raw materials has to be studied more.

In this study, the use of CDW as a filler in composites was studied. Three types of composites were manufactured with different CDW filler contents. The effect of the addition of CDW on the mechanical properties and moisture properties of WPC was studied based on standard methods, and the experimental results were compared with reference values.

2. Materials and Methods

Materials

Four different composites were studied in this study: three made from mixed CDW material and one made without CDW as a reference. The CDW material consisted of wood, plastic films, cardboard, and mineral wool fractions. The reference composite, named as WF-PP, was made of wood fibers, PP as the polymer, a coupling agent and a lubricant. The three CDW composites, named as WF-rHDPE-CDW1, WF-rHDPE-CDW2 and WF-rHDPE-CDW3, were manufactured with equal amounts of a polymer (recycled high density PE, rHDPE), a coupling agent and a lubricant as in the reference.

The thermoplastic matrix in the CDW composite was commercially available recycled high density polyethylene (rHDPE) supplied by L&T Muoviportti Oy by the trade name RecyPE HDPE 8 blue. The density of the rHDPE was 0.96 g/cm^3 and the melt flow index 8 g/10min (190^{o}C/2.16 kg). The coupling agent was an anhydride modified polyethylene (MAPE), Fusabond® E226 (DuPont).

In the reference composite, polypropylene (PP) Eltex P HY001P, with the density 0.91 g/cm^3 and melt flow index 45 g/10min (230^{o}C/2.16kg), supplied by Ineos Polyolefins, was used. The coupling agent in the reference composite was maleated polypropylene (MAPP) Orevac® CA 100 (Atofina). Struktol TPW 113 was used as the lubricating agent both in the CDW composites and the reference composite.

The wood fiber (WF) used in the reference composite was spruce (*Picea abies*) saw chips with the mean density of 1.58 g/cm^3. According to sieve analysis, the weighted average for the fiber length was 1.6 mm.

The CDW material was received from two separate construction sites in order to find out the effect of different blends of mixed waste on the composite properties. One of the sites was the renovation site of an old apartment building, and the other one was a construction site of a new building (Fig. 1). In composite WF-rHDPE-CDW1, the CDW was from the renovation site, while in composites WF-rHDPE-CDW2 and WF-rHDPE-CDW3, the CDW was generated in the new building construction site. Therefore the amount of packaging materials, such as cardboard and plastic film, in WF-rHDPE-CDW2 and WF-rHDPE-CDW3 was clearly higher than in WF-rHDPE-CDW1. Table 1 presents the composition of the WPCs based on the estimated proportions of materials in the CDW.

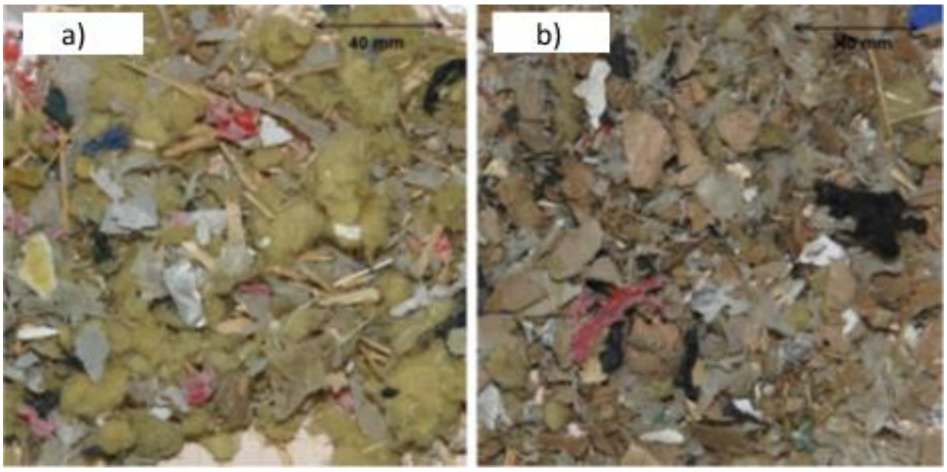

Fig 1. Presorted CDW material from separate construction sites; a) waste load from a renovation site, and b) waste load from a new building construction site.

Table 1. Composition of the studied WPCs based on estimated proportions of materials in the CDW fractions. [wt%]

	WF-rHDPE-CDW1	WF-rHDPE-CDW2	WF-rHDPE-CDW3	WF-PP
Wood fiber (WF)	44	44	-	64
Polymer	30	30	30	30
Coupling agent	3	3	3	3
Lubricating agent	3	3	3	3
CDW	20	20	64	-
Cardboard	*2*	*11*	*35*	
Wood	*8*	*2*	*6*	
Mineral wool	*6*	*2*	*5*	
Plastic film	*4*	*6*	*18*	

In composites WF-rHDPE-CDW1 and WF-rHDPE-CDW2, CDW filler content of 20 wt% was used in order to examine the effect of the origin of the CDW on the composite properties. The filler content of the WF-rHDPE-CDW3 composite was 64 wt% in order to find out the impact of an extremely high filler content on the composite properties.

The CDW obtained from a local waste processing plant was manually pre-sorted to remove metals and other unwanted materials, such as polystyrene (PS) and polyvinylchloride (PVC) plastic, and then crushed with an Untha LR630 single-shaft shredding system. Mechanical separation of the crushed CDW into different fractions according to particle size was performed with a commercial sorting equipment consisting of a roller screening and an air separator unit.

After mechanical sorting, the separated CDW fractions (Fig. 1) containing wood, plastic film, cardboard, and mineral wood were mixed and then agglomerated by using a Plasmec TRL-100/FV/W mixing plant. The agglomerates were crushed with a 4 mm mesh hammer mill Nirvana FH 6-4-75. The densities of the crushed agglomerates were measured to be 490 kg/m^3 for WF-rHDPE-CDW1, 466 kg/m^3 for WF-rHDPE-CDW2, and 478 kg/m^3 for WF-rHDPE-CDW3.

Wood-plastic composite manufacturing

The composites were manufactured with a counter-rotating conical twin-screw extruder, Weber CE7.2, equipped with a gravimetric feeding system by ConPro. The hollow profiles were extruded through a rectangular die (Fig. 2) at melt pressure 42 Pa and melt temperature 170^{o}C. The material output was 20 kg/h.

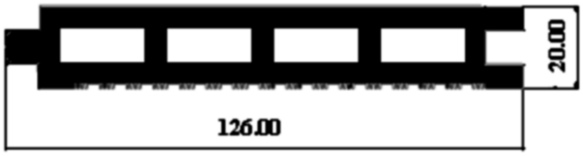

Fig.2. Hollow profile of extruded WPC

Analysis

The composite samples for flexural strength and modulus, hardness (Brinell), water absorption, and thickness swelling 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 WPC profile (Fig. 2). The dimensions of the samples were according to standards. All the mechanical and physical tests were carried out with 20 sample replicates.

The flexural and tensile properties and hardness were measured in accordance with standards EN 310, EN ISO 527-1 and EN 1534 on a Zwick/Roell Z020 tester. The Charpy impact strength for the un-notched samples was determined with a Zwick 5102 tester in accordance with the method ISO 179-1/1fU. The Charpy impact strength was calculated according to the following equation:

$$a_{cU} = \frac{E_c}{h \times b} \times 10^3 \quad (1)$$

where E_c is the corrected energy, in joules, absorbed by breaking the test sample; h is the thickness, in millimeters, of the test sample; and b is the width, in millimeters, of the test sample.

The water absorption (WA) and thickness swelling (TS) of the WPCs were measured according to the procedure described in standard EN 317. Water absorption and thickness swelling were calculated according to the following equations:

$$WA = \frac{(M_e - M_o)}{M_o} \times 100 \quad (2)$$

where M_e is the mass of the sample after immersion, g, and M_o is the mass of the sample before immersion, g.

$$TS = \frac{(T_e - T_o)}{T_o} \times 100 \quad (3)$$

where T_e is the thickness of the sample after immersion, mm, and T_o is the thickness of the sample before immersion, mm.

3. Results and Discussion

Table 2 shows the mechanical properties of the composites. Statistical significance between the reference and CDW composite samples data was tested by using Daniel's XL Toolbox Excel software. The data was analyzed by using the one-way ANOVA Bonferroni-Holm post hoc testing algorithm. Compared to the reference composite WF-PP, the addition of CDW weakened the mechanical properties by 10 to 25 %, and for the Brinell hardness as much as by 50 to 80 %, depending on the CDW filler content of the composite. One exception was the Charpy impact strength, which increased significantly when the CDW filler was added and as the amount of filler content increased. For all the mechanical properties, except tensile strength of WF-rHDPE-CDW2, it was found statistically significant differences. The results revealed that the mechanical properties were not directly dependent on minor variations in the composition of the CDW. Nevertheless, increasing the CDW filler content of the composite from 20 to 64 wt% appeared as noticeably lower hardness, as well as tensile and bending modulus of WF-RHDPE-CDW2. The effect on the other mechanical properties was minor, which might be a result of the high proportion of cardboard fraction in the CDW2 mixture, where cardboard worked as a substitute for wood fibers and thus improved the strength properties. In addition, a larger amount of plastic materials in WF-rHDPE-CDW3 appeared as the highest impact strength value of all tested composites, about 20 % higher than those of WF-rHDPE-CDW1 and WF-rHDPE-CDW2.

Table 2. Mechanical properties of the composites; s and ns denote statistically significant and no significant changes with 95% confidence level.

	WF-rHDPE-CDW1	WF-rHDPE-CDW2	WF-rHDPE-CDW3	WF-PP
Bending Strength [MPa]	20.93 ± 1.34 ^{s}	21.67 ± 0.67 ^{s}	20.15 ± 0.95 ^{s}	23.35 ± 1.20
Bending Modulus [GPa]	3.63 ± 0.15 ^{s}	3.32 ± 0.11 ^{s}	2.03 ± 0.09 ^{s}	4.44 ± 0.17
Tensile Strength [MPa]	15.95 ± 0.73 ^{s}	16.76 ± 0.71 ^{ns}	13.29 ± 1.65 ^{s}	19.50 ± 1.33
Tensile Modulus [GPa]	4.38 ± 0.17 ^{s}	4.00 ± 0.15 ^{s}	2.25 ± 0.21 ^{s}	6.00 ± 0.46
Brinell Hardness [HB]	7.26 ± 0.76	6.83 ± 0.93	3.00 ± 0.29	13.10 ± 2.00
Impact Strength [kJ/m^2]	4.13 ± 0.43 ^{s}	4.26 ± 0.19 ^{s}	5.08 ± 0.61 ^{s}	2.07 ± 0.13

The mechanical properties of studied CDW composites are consistent with the earlier studies concerning the use of recycled or waste material in WPCs. In a study of Moreno and Saron [21], the tensile strength of recycled LDPE waste-pine wood waste composite with 30 wt% of fiber loading was measured to be 12.3 MPa, and the tensile modulus 0.86 GPa, respectively. Turku et al [25] reported that tensile strength varied in the range of 10–12.5 MPa, and the tensile modulus between 2.5 and 3.5 GPa. In addition, the bending properties, hardness and impact strength were similar to the corresponding values obtained for a wood flour-recycled PE/PP blend composite with 54 wt% of fiber loading. On the other hand, if comparing the mechanical properties of WF-rHDPE-CDW composites to the corresponding values of Ratanawilai and Taneerat [33] for HDPE-rubberwood flour composites it can be observed the use of recycled HDPE as well as the addition of a CDW filler had a minor negative impact on the mechanical properties of WPCs. Najafi et al [34] studied composites made from sawdust and recycled PE and PP, and they found that the mechanical properties of specimens containing recycled plastics (HDPE and PP) were statistically comparable with those of composites made from virgin plastics. Also they observed that composites made from the mixture of HDPE and PP (both virgin and waste) provided tensile properties comparable to those made from HDPE or PP.

Table 3. Water absorption and thickness swelling of the composites; s and ns denote statistically significant and no significant changes with 95% confidence level (after 28 days of immersion)

	WF-rHDPE-CDW1		WF-rHDPE-CDW2		WF-rHDPE-CDW3		WF-PP	
Time [d]	TS [%]	WA [%]	TS [%]	WA [%]	TS [%]	WA [%]	TS [%]	WA [%]
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.48 ± 0.30	3.54 ± 0.26	0.30 ± 0.13	2.92 ± 0.35	0.14 ± 0.21	3.52 ± 0.54	0.69 ± 0.13	3.35 ± 0.11
7	2.07 ± 0.35	10.59 ± 0.45	0.97 ± 0.18	8.52 ± 1.28	0.37 ± 0.35	8.26 ± 0.82	2.48 ± 0.21	9.13 ± 0.19
14	2.91 ± 0.35	14.37 ± 0.51	1.50 ± 0.25	12.18 ± 0.98	0.72 ± 0.22	11.81 ± 0.47	4.51 ± 0.22	14.86 ± 0.41
28	4.44 ± 0.42 s	18.17 ± 0.52 s	2.56 ± 0.34 s	14.17 ± 1.01 s	1.26 ± 0.22 s	15.20 ± 0.48 s	6.93 ± 0.20	19.18 ± 0.21

The moisture properties of the tested materials are presented in Table 3. The water absorption and thickness swelling of the composites decreased significantly with the addition of the CDW filler. Over the 28 days of immersion in a water bath, the reference composite had WA of 19.18 % and TS of 6.93 %. For WF-rHDPE-CDW2 and WF-rHDPE-CDW3 composites, WA was measured to be 20–25 % lower. Respectively, TS reduced by over 60 % for WF-rHDPE-CDW2 and even 80 % for WF-rHDPE-CDW3. For WF-rHDPE-CDW1, the decrease of WA and TS was less pronounced. After 28 days of immersion, there were a statistically significant difference in WA and TS between all the composites at 95% confidence level. The results were similar to the findings of Turku et al [25] who reported that after immersion of 28 days WA varied in the range of 10–20 %, and TS in the range of 1–4%. Also they noticed that immersion period of 28 days was not enough to stabilize WA and TS parameters.

The moisture resistance properties are the most important characteristics of WPCs exposed to environmental conditions, determining their end-use applications [9]. WA and TS are strongly dependent on the material composition of the wood-plastic composite. The proportion of hydrophilic materials, such as wood fiber and cardboard, affects the moisture properties of the composite directly, i.e. WA and TS increase with the content of hydrophilic material. For example, Stark [35] verified the significant increase in the moisture absorption of wood flour-PP composite when fiber content was increased, and because of this, the flexural and tensile properties were also decreased. Moreover, the degradation of mechanical properties reduces the durability of WPCs. Identical results were found in study of Mrad et al [36] for injection molded wood-plastic composite (WPC) made with industrial wood residues.

As a hydrophobic material, polymer does not absorb water, but forms a protective barrier against moisture absorption for the wood particles encapsulated in the polymer matrix. Therefore, moisture absorption occurs mainly in the wood component exposed on the surface of the composite, or as a result of breakage or cutting [14,35]. The loss of adhesion at the matrix/wood interface leads to poor stress transfer at the interface and pathways for moisture uptake and biological attack [37]. Therefore, optimization of the type and amount of coupling agent is beneficial for improving the mechanical and moisture properties of WPCs made of recycled thermoplastics. In composites made from a variety of recycled thermoplastics, the use of more than one type of coupling agent could be useful to increase the interfacial bonding between wood fiber and polymer, and thus improve the durability of the composite [38].

The effect of mineral fillers on the moisture resistance of WPCs has been studied widely. In addition to improved moisture properties, the use of mineral fillers enhances the mechanical properties and thermal resistance, as well as maintains good dimensional stability in composites. Väntsi & Kärki [31] have studied the use of mineral wool as a filler in WPCs, and they reported the addition of mineral wool increased the moisture resistance properties of composites significantly. WA decreased by 32-67 % and thickness swelling by 27-73 % when 20-40% of recycled mineral wool was added to the composites. In the present study, the proportion of mineral wool in the CDW mixture was around 5 %, and therefore the effect on the moisture resistance properties was lower.

Keskisaari et al. [32] have studied the use of CDW as a mineral filler in composites with identical material composition as in this study. In their study, the CDW material was burned at 800 ºC in order to remove organic contaminants. When comparing the results of the studies, it can be observed that there were no major differences in the moisture resistance of the composites even when the organic contaminants, such as wood or wood-based materials, were eliminated from the CDW mixture. The mechanical properties of the composites were slightly lower than in this study due to the fact that wood fibers do not exist in burned CDW.

4. Summary

In this study, wood-plastic composites containing construction and demolition waste were manufactured by extrusion, and their mechanical and moisture properties were studied.

The mechanical tests indicated that the addition of a CDW filler decreased the tensile and bending properties, as well as the hardness of the composites, while the Charpy impact strength was observed to increase with an increase in the CDW filler content. Water absorption and thickness swelling as moisture properties were generally decreased by the addition of the CDW filler.

The effect of variation in the material composition of CDW and the amount of filler content in the composites was also studied. A minor variation in the material composition of the CDW did not have a significant effect on the mechanical performance between the composites having an equal filler content, whereas the filler composition appeared to have an impact on the moisture properties of the composites. A greater filler loading did not appear as a greater decrease in the composite properties. The greater loading even improved the Charpy impact strength considerably. Of the moisture properties, the greater filler loading increased TS, but for WA there was no difference compared to the lower filler content used in this study.

Considering the quality of raw material, the properties of CDW composites were at an acceptable level. Thus, the utilization of CDW as a filler in composites has great potential if suitable applications are found. A suggestion for further research could be a search for new applications widely, not only in the field of composite manufacturing. Changes in the composition of CDW create challenges for the utilization of WPCs in different end-use applications. As well as the adhesion and cohesion between the coupling agent and other components in WPC with CDW filler would be significant to research.

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