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CEMENT-BONDED WOOD PANELS FILLED WITH DUROPLAST SANITARY WARE WASTES

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ABSTRACT

The effect of using duroplast sanitary ware waste as a substitute for wood materials in cement-bonded wood panels was evaluated. Utilizing these wastes can provide considerable economic and environmental benefits by reducing the use of wood materials and the deposits in landfills. Cement-bonded wood panels were produced with the replacement of spruce wood materials by the duroplast sanitary ware waste particles in 10 wt%, 20 wt%, 30 wt%, and 40 wt%. The produced panels were examined in terms of physical, thermal, mechanical, and morphological properties and compared with the related standards. Experimental findings demonstrated that water absorption, moisture content, and thickness swelling values of the panels were enhanced by the addition of duroplast sanitary ware waste. The duroplast sanitary ware waste did not affect the density of the panels. The bending strength and the modulus of elasticity of the cement-bonded wood panels can be increased up to 23 % and 5,6 %, respectively, by the addition of 10 wt% duroplast sanitary ware waste particles. However, the internal bond strength and the screw withdrawal resistance values were reduced by an increment in the use of duroplast sanitary ware waste. The scanning electron microscope observation revealed that there was no mechanical interlocking between the duroplast sanitary ware waste and cement, and the formations of voids in the panels increased with an increase in the duroplast sanitary ware waste particle content. The thermal analysis showed that the use of duroplast sanitary ware waste resulted in increased cement hydration products due to the reduction in the wood content of cement-bonded wood panels.

Keywords: Cement-bonded wood panels, duroplast sanitary ware wastes, mechanical properties, morphological properties, physical properties, thermal properties.

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INTRODUCTION

Rapid urbanization, expansion of industrialization, population growth, and changes in consumption habits lead to the depletion of natural resources and the vast amount of industrial waste generation, which causes increased environmental and socioeconomic problems (Negash *et al.* 2021, Hansted *et al.* 2023). Reuse or recycling of industrial wastes can strongly contribute to a considerable reduction in the amount of waste deposited into the environment, production cost, energy consumption, use of natural resources, and greenhouse gas emissions (Klimek *et al.* 2020, Maljaee *et al.* 2021).

One of these wastes is sanitary ware waste, which is classified as a non-biodegradable material, originating from construction, demolition, and industrial activities. Sanitary waste encompasses a diverse array of materials, predominantly composed of ceramic, metal, plastic, and composite substances. This category includes various fixtures such as toilet bowls, wash basins, bathtubs, bidets, as well as accompanying elements like ceramic tiles, brass and stainless steel taps, valves, shower accessories, tank lids, siphon covers, and duroplast (thermoset plastic) bathroom furniture (Halicka *et al.* 2013, Roushdy 2019, Hossain and Roy 2020).

These wastes can be utilized as filler materials in the construction industry for products such as concrete, bricks, and asphalt (Halicka *et al.* 2013, Roushdy 2019), as a raw material source in ceramic production, and the duroplast waste can be used as a filler in polymer composite manufacturing as well as for energy recovery through appropriate incineration (Hossain and Roy 2020).

Several researchers have successfully examined the utilization of sanitary ware wastes as aggregate in cement-bonded composites (Klimek *et al.* 2020, Medina *et al.* 2011, Halicka *et al.* 2013, Ortigara *et al.* 2022). Medina *et al.* (2011) investigated some properties of concrete produced with recycled ceramic waste from sanitary ware as a partial replacement of natural coarse aggregates (15 %, 20 %, and % 25). They concluded that the ceramic wastes of sanitary ware increased the mechanical properties of the concrete but did not change its physical properties and that the properties of these concretes produced were suitable for structural purposes.

A study by Halicka *et al.* (2013) on the utilization of ceramic sanitary ware wastes as aggregate in concrete indicated that high-performance concrete could be obtained using ceramic sanitary ware wastes. Farinha *et al.* (2015) found that coating mortar made by adding ground fine sanitary ware aggregates had better performance than the reference mortar. Klimek *et al.* (2020) investigated the effect of using aggregate from sanitary ceramic waste on the performance of stucco mortars and reported that using sanitary ceramic waste in the mortars led to a reduction in water uptake capacity and a significant increment in tensile strength and compressive strength.

According to García-González *et al.* (2015), substituting coarse aggregate made from waste ceramic sanitary ware for conventional aggregate when making structural concrete had no negative effect on the concrete's mechanical performances such as tensile splitting strength, tensile strength, and compressive strength. The data reported by Almeida *et al.* (2019) indicated that there was poor adhesion between the mortar and the ceramic aggregate from sanitary ware waste due to the glazing in the contour of the recycled aggregate. Reig *et al*. (2022), who investigated the ceramic sanitary ware (CSW) waste's pozzolanic activity in Portland cement-based mortars, concluded that the CSW waste facilitated Portland cement hydration reaction and significantly contributed to the mortars' strength development after 90 days of curing.

Another waste type is plastics, generally made of thermoplastic or thermosetting polymers (Raad and Assaad 2022). Thermoplastics, including polyvinyl chloride, polyethylene terephthalate, polypropylene, high and low-density polyethylene, and expanded polystyrene are valuable materials since they can be recycled by melting (Panyakapo and Panyakapo 2008, Dweik e*t al.* 2008). Thermosets, generally known as unrecycled and non-biodegradable materials, such as epoxy resin, urea-formaldehyde, unsaturated polyesters, phenol-formaldehyde, melamine formaldehyde, and polyurethanes are widely utilized in aerospace applications, civil structures, automotive parts, and electronic equipment (Jin *et al.* 2019, Chen *et al.* 2023).

These thermoset-based products, which are produced approximately 65 million tons per year, generate a huge amount of waste generally dumped into landfills (Kazemi *et al.* 2021, Chen *et al.* 2023). These thermoset wastes, which are currently disposed of by either burning or burying, are quite harmful to the environment due to their long-lasting non-degradable structure and toxic chemical contents. To overcome this problem, recycling thermoset wastes is known as a favorable solution. However, compared to thermoplastic waste, the recycling and reusing possibilities of thermoset plastic wastes are very limited due to their infusible and insoluble properties (Raad and Assaad 2022). The evaluation of these wastes is of critical issue in terms of reducing environmental pollution, increasing their economic value, and protecting natural resources, and there are few studies on this subject.

Wood in different forms, such as chips, flakes, strands, fibers, or wood wools is often used as reinforcement/filler material to enhance the bending strength, fracture toughness, and ductility properties of cement-bonded composites due to their outstanding features such as the enhanced biodegradability, the ease of production, and the low density (Caprai *et al.* 2018, Akinyemi and Dai 2020). Cement-bonded wood panels are reconstituted wood products that have life-cycle economy, fire resistance, and good longevity (Soroushian *et al.* 2013). Their performance depends on the cement's amount and type and the wood properties.

The bonding mechanism between cement matrix and wood can be affected by numerous factors, such as the tree species, the tree harvest time, the wood storage conditions, the cement composition, the water/cement ratio, the wood geometry, the wood/cement ratio, and the curing conditions (Caprai *et al.* 2018). Among other factors, the processing and properties of cement-bonded wood panels are very susceptible to specific wood species (Soroushian *et al.* 2013). The alkaline-soluble substances in wood inhibit or delay the cement hydration reaction, which leads to an excessive decline in the mechanical performance of cement-bonded wood panels (Wang *et al.* 2016).

Previous studies demonstrated that some wood substitutes such as polypropylene plastic (Ohijeagbon *et al.* 2020), chicken feather (Adediran *et al.* 2021), microcrystalline cellulose (Donmez Cavdar *et al.* 2022), seagrass fiber (Mayer *et al.* 2022), and pumice powder (Aras *et al.* 2021) have a positive influence on the Portland cement hydration due to a reduction in the content of inhibitory alkaline-soluble substances in cement-bonded wood panels. However, the physico-mechanical performance of cement-bonded wood panels could be negatively affected by the use of wood substitutes above a certain rate due to some undesirable factors, such as weak cement-substitute material bonding, low compaction ratio, high specific surface area, low slenderness ratio, and high bulk density.

Nanocellulose fibers were found to enhance the cement hydration degree and the performance of cement-bonded composites (Cao *et al.* 2016, Akhlaghi *et al.* 2020, Donmez Cavdar *et al.* 2022). Nazerian *et al.* (2011) examined the effects of the use of residues from trimming cement-bonded wood panels on the strength of cement-bonded wood panels and concluded that these residues have a lower hydration-retarding effect and are more compatible with cement due to the particles that the hardened cement penetrated and coated, compared to natural wood particles. They also reported that the 6 % residue addition considerably improved the mechanical performance of the cement-bonded wood panels.

On the other hand, Amiandamhen *et al.* (2021), who produced cement-bonded panels using tyre fibers and wood residues, reported that tyre fibers caused a decrease in the strength values of cement-bonded panels due to the low modulus of tyre fibers and the poor interfacial adhesion between cement hydration products and tire fibers.

Duroplast sanitary wares are made from urea formaldehyde molding compound granules through high pressure and temperature by a compression molding machine to mold into shape (Figure 1). The main components of urea formaldehyde molding compounds are urea formaldehyde resin and cellulose. To the best of our knowledge, no research on the utilization of duroplast sanitary ware wastes in cement-bonded wood panel production has been reported. This work aimed to explore the feasible utilization of duroplast sanitary ware wastes in the production of cement-bonded wood panels.

MATERIALS AND METHODS

Materials

Duroplast sanitary ware wastes DSWs (toilet seat and cover wastes) were collected from a dump of Turkish factory manufacturing sanitary ware products in Turkey (Figure 1). Spruce (*Picea orientalis* L.) was provided by the Artvin Coruh University's Furniture Workshop in Turkey. The spruce wood and the DSWs were initially hummer milled into particles and the dust and oversize particles were then screened out. The DSW and the spruce particles retained on a 0,5 mm sieve and passed through a 3 mm sieve were used for the cement-bonded wood panel production. CEM II 32,5 R type Portland cement supplied by Askale Cement Co. (Turkey) was used as a mineral binder in this investigation. To reduce the spruce wood particles' inhibitory effect on the cement hydration, calcium chloride ($CaCl_2$) was employed at 5 % w/w of the cement for all panel types. Calcium chloride replaced an equivalent weight of cement.

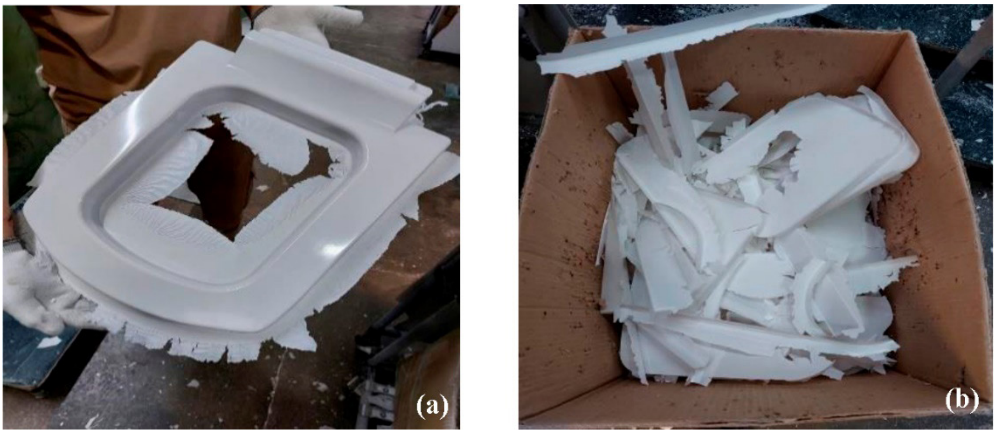

Figure 1: (a) Freshly demoulded duroplast toilet seat and (b) Its edge-trimmed residues.

Cement-bonded wood panel production

The replacement ratio of wood materials by DSWs and the production parameters used in the cement-bonded wood panels are depicted in Table 1. Wood-cement ratio (w/c) of 1:3, specific gravity of 1200 kg/m^3, Water-cement ratio (w/c) of 0,61, and addition of 5 wt% $CaCl_2$ were constant for all the panels. For the production of panels, Portland cement, water, wood particles, DSW particles, and calcium chloride solution (accelerator) were mixed by a mechanical mixer. The mixture was then hand-formed into a compact-laminate mold with 450 mm × 450 mm x 10 mm. Afterwards, the formed mats were compressed by a hot press at 18-20 kg/cm^2 pressure for 24 h. A study by Yel *et al.* (2020) showed that the highest performance for spruce-based cement-bonded wood panels was reached at a pressing temperature of 60 °C. Therefore, in this study, a temperature of 60 °C was applied in the first 8 hours of the compression process. After 24-h compression process, the cement-bonded wood panels were transferred to a climate room at 20 °C and 65 % relative humidity for 28 days. Three replicated test panels were produced for each condition. After 28 days of curing, the conditioned panels were cut by a circular saw into test specimens according to the relevant standards.

Table 1: Process variables of the cement-bonded wood panels.

Panel Types	DSWs (wt%)	Wood particles (wt%)	Production parameters
W0	0	100	Panel sizes: 450 mm x 450 mm x 10 mm Wood-cement ratio: 1/3 The target panel density: 1200 kg/m^3 Cement curing accelerator: $CaCl_2$ (5 % w/w of the cement) Press pressure: 18-20 kg/cm^2
W10	10	90	
W20	20	80	
W30	30	70	
W40	40	60	

Determination of physical and mechanical properties

The moisture content (MC) of specimens was determined according to EN 322 (1993) standard, and density was evaluated by EN 323 (1993) standard. Dimensional stability test was conducted on the specimens with the size of 50 mm x 50 mm x 10 mm, submerged under distilled water for 24 h, in accordance with EN 317 (1993) standard. Water uptake test was carried out according to ASTM D1037 (2006) standard.

The flexural strength tests were performed in compliance with EN 310 (1993) standard. Moreover, screw withdrawal resistance (SWR) and internal bond strength tests were done following EN 320 (2011) and EN 319 (1993) standards, respectively. All the mechanical tests were performed on a Zwick Roel Z050 Universal Testing Machine.

Determination of thermal properties (TGA-DTG)

For the thermal analysis, the specimens were prepared by grinding, sieving, and then drying to a constant weight at 55 °C ± 3 °C. The PerkinElmer STA 6000 Thermogravimetric analyzer was used to perform the thermogravimetric (TGA) and derivative thermogravimetric (DTG) analyses. In a nitrogen atmosphere, the device was programmed to heat up at a rate of 10 °C per minute from 40 °C to 900 °C. W0, W20, and W40 panels were selected to determine the influence of DSW particles on the thermal characterization of the panels by TGA/DTG analysis.

Determination of morphological properties (SEM-EDS)

The samples fractured from cement-bonded wood panels were dried at 50 °C and then coated with gold for 181 s before scanning electron microscope (SEM) observation. Micrographs and elemental compositions of the fractured surface of selected panels were acquired by an SEM (Carl Zeis EVO LS 10) coupled with an energy-dispersive spectroscopy detector (Bruker Quantax XFlash 6/100).

Statistical analysis

To compare the means of panel groups, the data obtained from mechanical and physical tests were subjected to analysis of variance (One-Way ANOVA) using the SPSS 21.0 package software (SPPS 2020). Duncan's test was applied to determine homogeneity groups as the difference between the means of the panel groups was significant ($p < 0,05$).

RESULTS AND DISCUSSION

Mechanical properties

Table 2 presents the results of mechanical tests with statistical analysis performed on the DSWs-added cement-bonded wood panels. An increment of 23 % for modulus of rupture (MOR) and 5,6 % for modulus of elasticity (MOE) was recorded for W10 panels (10 % DSWs) when compared with the control panels (without DSWs). These improvements in MOR and MOE can be attributed to the fact that the DSW particles have a low inhibitory effect on cement hydration reactions in comparison with spruce wood because the total amount of inhibitory alkali-soluble substances in the panels containing DSWs is much lower than that in the panels containing 100 % spruce wood particles.

The panels made using DSW particles as a substitute for spruce wood particles had more hydration products than the panels produced with 100 % spruce wood because the DSW particles contained lower soluble polymers compared to spruce wood particles. This situation was confirmed by the results of TGA and EDS. A similar statement was made by Nazerian *et al.* (2011) who reported that the trimming residues of cement-bonded wood panels, compared to natural wood particles, improved the degree of cement hydration reaction and the cement-bonded wood panels' mechanical performance due to wood particles penetrated and coated by hardened cement. Additionally, the specific surface area of particles is well known to significantly affect the properties of cement-bonded wood composites (Nazerian *et al.* 2011). The DSW particles replacing natural spruce wood particles decreased the specific surface area of the particles in the panels because the DSWs have a much higher density than the spruce wood, resulting in the increased cement content per unit surface area. Therefore, this may have contributed to the improved mechanical performance of panels.

It was also noticed that the use of DSW particles at high dosages (30 % and 40 %) as wood replacement caused respectively 22 % and 31 % reductions in the panels' MOR values compared to the control panels (W0). Moreover, the internal bond strength (IB) and the screw withdrawal resistance (SWR) values were reduced with an increase in the DSWs content of panels. The lower the particle bulk density, the higher the panel compaction ratio, leading to the production of high-strength panels (Xing *et al.* 2006, Nazerian *et al.* 2011). The densities of DSW and spruce wood particles used in this study were measured as 1,52 g/cm^3 and 0,42 g/cm^3, respectively. Due to the higher density of DSWs compared to spruce wood, the compression ratio of the panels decreased as the DSW content increased, which led to a weak bond strength between the DSW/wood particles and the cement matrix.

The undesirable properties of DSW particles, such as low aspect ratio, hydrophobic structure, low permeability, and high density compared to wood, led to the low compaction ratio and the weak DSWs-cement matrix bond strength in the panels (Saikiaa and Brito 2013). In addition, the poor interfacial adhesion between the DSW particles and the cement hydration products as well as the geometry and density values of DSWs can be the reason for the reduced mechanical performance of panels.

A study by Dweik *et al.* (2008) showed that the use of up to 30 % melamine formaldehyde waste as a substitute for sand significantly improved the concrete's mechanical properties, and the concrete's mechanical properties were reduced with a further increase in melamine formaldehyde waste proportion. Panyakapo and Panyakapo (2008) reported that the use of high proportions of melamine plastic waste as sand replacement led to a bonding problem between the cement matrix and melamine plastic waste, resulting in a reduction in the concrete's mechanical performance. Fiore *et al.* (2014) and Khern *et al.* (2020) concluded that tire rubber caused a reduction in the strength values of cement composites due to poor interfacial adhesion between cement hydration products and tire rubbers. Gu and Ozbakkaloglu (2016) and Chen *et al.* (2023) stated that poor interface bonding between thermoset wastes and cement matrix led to the reduced mechanical performance of cement-bonded composites.

The porous structure and rough surface of wood strongly contribute to the formation of mechanical interlocking between the cement hydration products and the wood particles (Hermawan *et al.* 2001). However, the surface of DSW particles is devoid of visible pores and depressions that could increase the contact surface and allow the cement matrix to penetrate the DSW particles. The nonporous structure and smooth surface of the DSW particles, unlike wood, prevented the formation of mechanical interlocking between the DSW particles and the cement hydration products.

The weak bonding between the cement hydration products and the DSW particles may have also been caused by poor physical and chemical interaction (Marques *et al.* 2021). Dweik *et al.* (2008) concluded that smooth particles of round-shaped thermoset plastic waste caused a poor interfacial bond between aggregates and cement matrix, resulting in reduced concrete strength. The voids and the weak interfacial adhesion of the DSWs-cement matrix in the panels upon the use of DSWs were confirmed by the SEM observations (Figure 3). Moreover, cement hydration reactions may be reduced on the surface of DSW particles because the hydrophobic structure of DSW particles (unlike wood) repels water molecules (Tayeh *et al.* 2021, Chen *et al.* 2023).

The mechanical test results were found to be consistent with the results of Ohijeagbon *et al.* (2020) and Dweik *et al.* (2008). The panels produced using the DSWs up to 20 wt% for MOR, 30 wt% for MOE, and 40 wt% for IB strength satisfied the minimum requirements (9 MPa for MOR, 4500 MPa for MOE and 0,5 MPa for IB) specified in EN 634-2 (2009).

Table 2: Means, standard deviations, and homogeneity groups of mechanical properties of the cement-bonded wood panels.

Panel Types	MOR (MPa)	MOE (MPa)	IB (MPa)	SWR (N/mm)
W0 (Control)	9,17C*± 0,51**	5506AB ± 294	1,09A ± 0,068	97,5A ± 8,53
W10	11,28A ± 0,76	5813A ± 423	1,02B ± 0,091	94,6A ± 4,89
W20	10,30B ± 0,65	5398B ± 214	0,81C ± 0,071	84,4B ± 7,92
W30	7,14D ± 0,67	4779C ± 290	0,75CD ± 0,067	69,7C ± 4,92
W40	6,33E ± 0,31	4066D ± 482	0,72D ± 0,062	65,2C ± 5,26
P values	0,001	0,001	0,001	0,001

MOR: Modulus of rupture; MOE: Modulus of elasticity; IB: Internal bond strength; SWR: Screw withdrawal resistance; p-value: Significant level; * The different letters show differences between the means and the same letters show no differences between the means (at 5 % significant level) **: Standard deviations

Physical properties

The results of physical tests with statistical analysis performed on the DSWs-added cement-bonded wood panels are presented in Table 3. The DSW particles did not have a statistically significant effect on the density values of cement-bonded wood panels. The water absorption values ranged from 16,9 % to 18,5 %, while the thickness swelling values ranged from 2,31 % to 2,31 % after 24-h immersion. The thickness swelling values were highest in the W0-panels (5,13 %) without the DSW particles and lowest in the W40-panels with 40 % DSW particles (2,31 %). The cement-bonded wood panels containing DSW particles exhibited lower moisture content and thickness swelling than those containing 100 % wood particles after being immersed in water for 24 hours. The moisture content and thickness swelling were significantly reduced with the increase in the panels' DSW particle content.

The hydrophobic structure of DSW particles repels water molecules, which leads to reduced moisture content and dimensional stability values in the panels with DSW particles (Tayeh *et al*. 2021). A study by Ohijeagbon *et al*. (2020) on the use of polypropylene plastic as a substitute for wood particles in the production of wood-cement composite boards indicated that the moisture content and water uptake values decreased as the polypropylene plastic content in the composite boards increased. The panels' moisture content and dimensional stability values in the present study are similar to what was reported by Ohijeagbon *et al.* (2020), Adediran *et al.* (2021), and Donmez Cavdar *et al*. (2016). In EN 634-1 (1999) standard, it is stated that the moisture content limit values for cement-bonded particleboards are 9 % ± 3 %. The moisture content values (6,32 % - 7,89 %) of all the panels met the standard requirement mentioned above. However, none of the panels met the maximum thickness swelling requirement (1,5 %) specified in EN 634-2 (2009) standard. This may be due to the high wood/cement ratio.

Table 3: Means, standard deviation, and homogeneity group of physical properties of the cement-bonded wood panels.

Panel Types	MC (%)	d (kg/m^3)	WA (%) 24 h	TS (%) 24 h
W0 (Contr.)	7,89A* ± 0,05**	1260A ± 23	18,5B ± 0,64	5,13D ± 0,26
W10	7,65B ± 0,25	1270A ± 17	18,4B ± 0,36	3,34C ± 0,32
W20	6,48C ± 0,23	1250A ± 44	18,1B ± 0,76	3,29C ± 0,09
W30	6,29C ± 0,18	1250A ± 32	17,8B ± 0,85	2,93B ± 0,20
W40	6,32C ± 0,28	1260A ± 27	16,9A ± 0,91	2,31A ± 0,21
P values	0,001	0,849	0,002	0,003

MC: Moisture content, d: Density, WA: Water absorption, TS: Thickness swelling, P value: Significant level,
* The different letters show differences between the means and the same letters show no differences between the means (at 5 % significant level), **: Standard deviation.

Thermal analysis (TGA-DTG)

The effect of the incorporation of duroplast sanitary ware wastes (DSWs) on the formation of cement hydration and carbonization products was elaborated using thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG). The results of TGA/DTG demonstrated that the DSW particles boosted the cement hydration process in Figure 2 and Table 4.

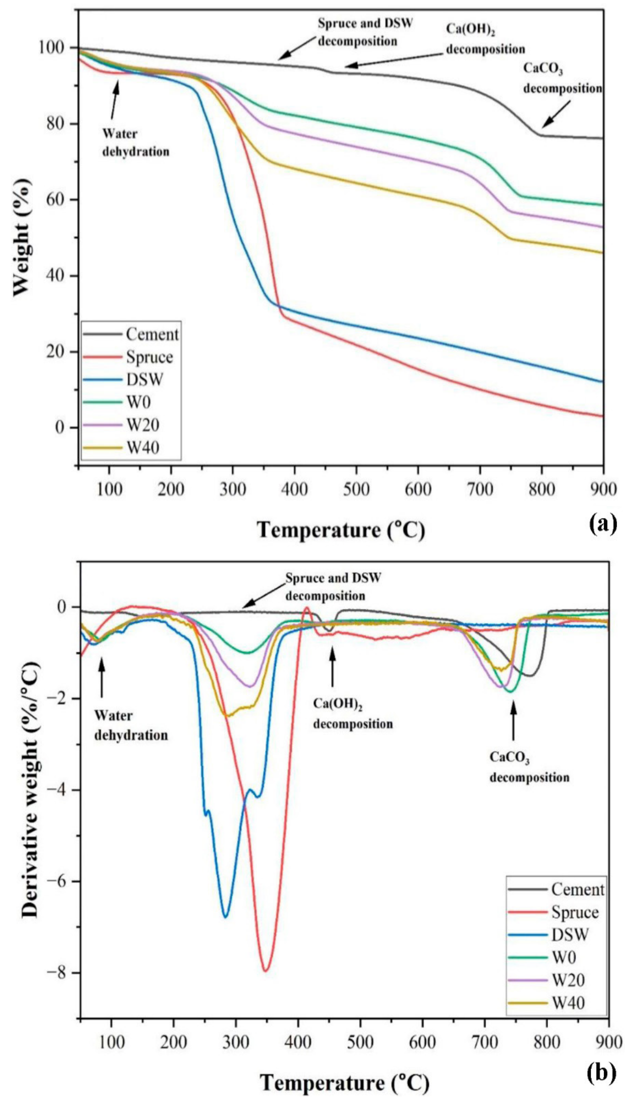

Figure 2: (a) TGA and (b) DTG curves of the cement-bonded wood panels.

Four endothermic peaks were observed in the TGA/DTG curves of the specimens, as can be seen in Figure 2. The first peak at the temperature range of 51 °C - 180 °C can be attributed to the dehydration of wood particles, ettringite, and calcium silicate hydrate (C-S-H). The second peak at the temperature range of 180 °C - 380 °C is related to the decomposition of wood components and DSW particles. The weight loss in the second peak significantly increased with an increment in the DSWs content of the panels (Figure 2 and Table 4). Moreover, the DSW particles caused a reduction in the second peak's inflection point. On the other hand, the amount of residue at 900 °C was reduced as the DSWs content increased.

The third peak at the temperature range of 380 °C - 520 °C is associated with the dehydroxylation of calcium hydroxide (portlandite), providing important information about the cement hydration degree. An increase in the DSW content of the panels resulted in increased weight loss at the third peak. The DSW particles improved the cement hydration reaction due to their much lower inhibitory substance content than the spruce wood particles. Therefore, this explains the improvement in the panels' bending properties upon the DSW particle addition. The last peak at the temperature range of 520 °C - 900 °C corresponds to the decarbonization of calcium carbonate ($CaCO_3$). The chemical reaction of CO_2 with the $Ca(OH)_2$ yielded $CaCO_3$, which is less soluble in water than $Ca(OH)_2$ (Soroushian *et al.* 2013). Due to the hydrophobic property of DSW particles, calcium carbonate formation was reduced in the W40-coded panels containing 40 % DSW particles.

Table 4: Weight loss in the cement-bonded wood panels obtained by TGA.

Samples	Weight loss (wt%)				Residue (wt%) at 900 °C
	First peak (51-180) °C	Second peak (180 - 380) °C	Third peak (380 - 520) °C	Fourth peak (520 - 900) °C	
Cement	2,12	2,39	2,32	16,87	76,14
Spruce	3,88	63,20	9,48	17,45	3,06
DSW	6,41	60,62	5,55	13,94	12,17
W0	5,11	10,74	4,25	19,94	58,61
W20	5,06	15,95	4,96	20,47	52,76
W40	5,18	24,84	5,35	17,68	45,99

Morphological and chemical characterization (SEM-EDS)

Figure 3 illustrates the micrographs of cement-bonded wood panels filled with the DSW particles. The SEM images indicated that the interface between the wood and the cement hydration products was well compacted, while the DSWs-cement matrix interface was loose. In addition, in contrast to the DSW particles, wood particles were well encapsulated with the cement hydration products, resulting in the better mechanical performance of the panels. Figure 3 also showed that there was no good interfacial adhesion and interlocking formations between the cement hydration products and DSWs in the W20 and W40 panels, resulting in decreased mechanical properties of the panels. A similar result was found by Raad and Assaad (2022), who reported a weak interface bond between the cross-linked polyethylene (XPE) plastic waste and the cement hydration products. A study by Almeida *et al.* (2019) indicated that there was a poor adhesion between the ceramic aggregate from sanitary ware waste and the mortar due to the glazing in the contour of the recycled aggregate. In another study, Khern *et al.* (2020) observed a weak interfacial adhesion between cement matrix and tyre rubber. Therefore, this also explains why the mechanical performance of panels containing a high amount of DSWs was decreased.

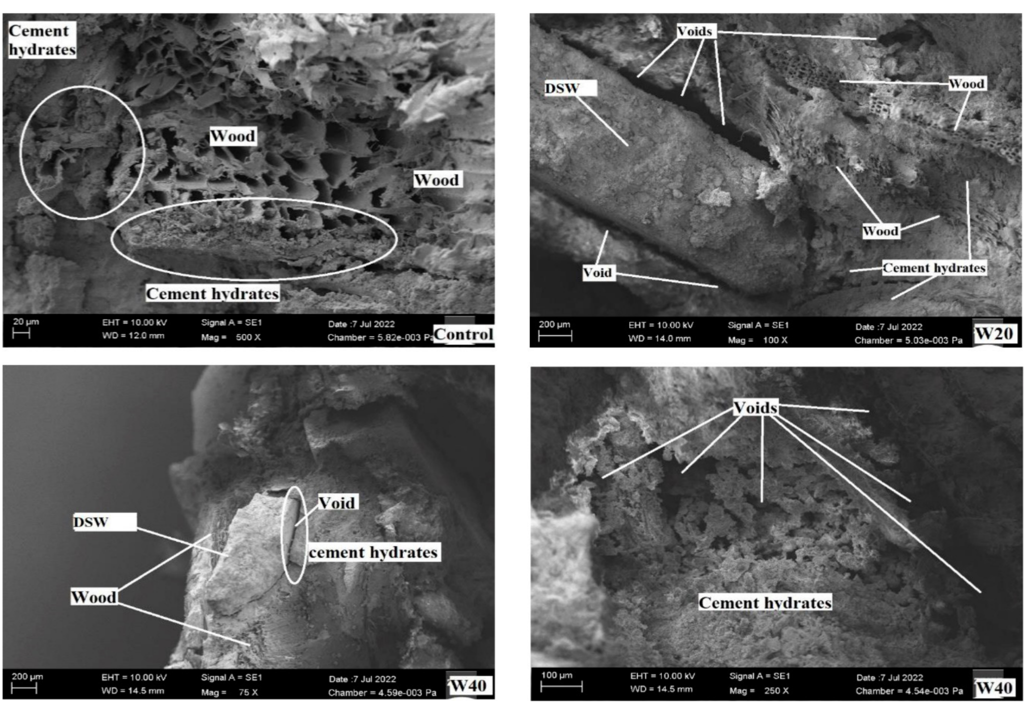

Figure 3: Micrographs of the fractured surfaces of cement-bonded wood panels at different magnifications.

Energy dispersive spectroscopy (EDS) analyses were performed on the micrographs of control and W20 specimens to identify the chemical composition. Figure 4 presents the chemical elements of the panels, which were calcium, silicon, iron, magnesium, carbon, oxygen, and aluminium, detected by EDS. The result of EDS analyses demonstrated that the panels had different elemental compositions, and DSWs-added panels contained higher amounts of calcium (Ca) and silicon (Si) than the control panels. This can be attributed to the fact that the DSWs-added panels have more cement hydration products (C-S-H and $Ca(OH)_2$) than the control panels due to the DSWs' low inhibitory effect on cement hydration reactions compared to the wood.

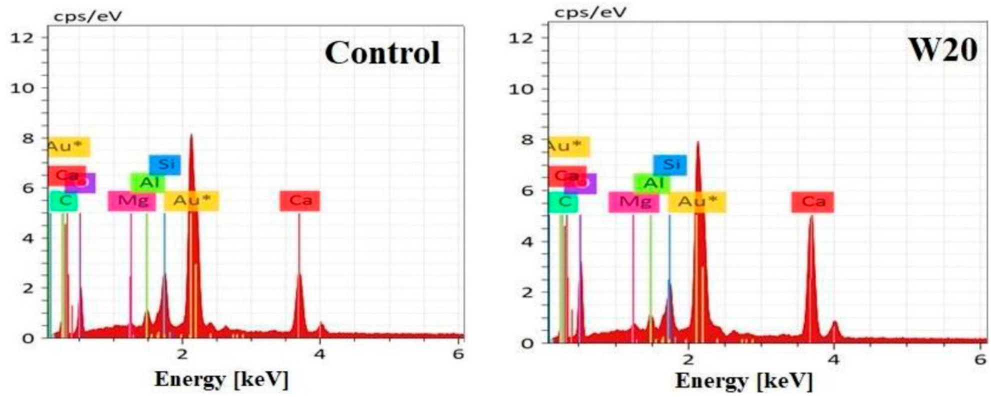

Figure 4: EDS spectral profiles of the cement-bonded wood panels.

CONCLUSIONS

The focus of this work was the utilization of duroplast sanitary ware wastes (DSWs) to partially replace wood particles in cement-bonded wood panels. The DSWs were used to replace wood particles by 10 wt%, 20 wt%, 30 wt%, and 40 wt% in the production of cement-bonded wood panels. The key conclusions to be drawn from the findings discussed in this article are set out below:

It is feasible to reuse duroplast sanitary ware wastes to produce cement-bonded wood panels with enhanced characteristics. The DSW particles can substitute for at least 20 % of wood particles in cement-bonded wood panels, following the mechanical requirements in EN 634-2 (2009). The maximum MOR and MOE values of the panels were achieved when 10% DSW particles were substituted for spruce wood particles.

By adding the DSW particles, the panels' moisture content and thickness swelling values were considerably reduced. However, the panels' density was statistically not influenced by the DSW particle addition.

Morphological analyses done by SEM indicated that, compared to the wood particles, there was a very weak interfacial adhesion between the DSW particles and the cement matrix, resulting in decreased mechanical properties of the panels.

The TGA/DTG results demonstrated that the panels made using DSW particles as a substitute for spruce wood particles had more hydration products than the panels produced with 100% spruce wood particles.
Utilization of DSW particles resulted in the loss of internal bond strength and screw withdrawal resistance in the panels.

Additional research is needed to determine the effects of other factors such as wood-cement ratios, water-cement ratios, panel density, tree species, and the chemical additive's type and ratio on the cement-bonded wood panels produced using the different sizes and densities of the DSW particles.

Authorship contributions

H. Y.: Conceptualization, methodology, validation, visualization, formal analysis, investigation, writing - original draft, writing - review & editing. U. A.: Investigation, visualization, writing – original draft, writing – review & editing. H. K.: Investigation, methodology, resources. R. A.: Investigation, resources.

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