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PERFORMANCE OF CEMENT-BONDED WOOD PARTICLEBOARDS PRODUCED USING FLY ASH AND SPRUCE PLANER SHAVINGS

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ABSTRACT

The aim of this research was to investigate the physico-mechanical, thermal, and morphological properties of cement-bonded wood particleboards produced by using fly ash as a partial cement replacement and spruce planer shavings. Experimental single-layer cement-bonded wood particleboards produced using a target density of 1200 kg/m^3, 1/3 wood-cement ratio, a dimension of 460 x 460 x 10 mm^3 and 5 %, 10 %, 15 %, 20 % fly ash as cement replacement were tested for physical and mechanical properties in accordance with EN and ASTM standards. Moreover, morphological and thermal properties of the cement-bonded wood particleboards were analysed by using the scanning electron microscope and thermogravimetric analysis-derivative thermogravimetry. Test results indicated that the fly ash enhanced both the bending strength and water-resistance of the cement-bonded wood particleboards. Internal bond and screw withdrawal strengths tended to decrease as the fly ash content increased in the cement-bonded wood particleboards, but this decrease was not statistically significant. As the fly ash increased, the weight loss of the cement-bonded wood particleboards decreased in the thermogravimetric analysis because of the pozzolonic reaction of the fly ash with calcium hydroxide. In the scanning electron microscope, it was observed that calcium silicate hydrate gel increased, whereas calcium hydroxide decreased as the usage ratio of the fly ash increased in the cement-bonded wood particleboards.

Keywords: Cement-bonded wood particleboards, fly ash, planer shavings, physic-mechanical properties, thermal-morphological properties.

INTRODUCTION

Cement-bonded wood particleboard (CBWP) has been widely used as various construction components for more than 100 years, because of their excellent properties such as high toughness, high durability, high impact resistance, dimensional stability, low water absorption, thermal insulation, freeze-thaw resistance, fire resistance (in both B1 and A2 class), good acoustic, biological degradation resistance (fungi, insects, termites, and vermin attacks), easy manufacturing and low manufacturing costs (Quirogaa *et al.* 2016, Donmez Cavdar *et al*. 2022). Cement-bonded wood particleboards perform very well in both interior and exterior uses such as wall cladding, roof sheathing, floor, fences, paving and sound barriers without any treatment (Okino *et al*. 2004, Aras *et al.* 2022).

In recent years, building sector has faced the challenge of incorporating sustainability into their manufacturing processes, either by exploring for new materials more eco-friendly or by reducing the amount of carbon dioxide emitted into the environment. The opportunity of incorporating waste from other industries in the manufacturing processes can contribute to the aim (Pereira *et al*. 2013). Many researches have been carried out on the utilization of waste materials to avoid the harmful effects to the atmosphere and to develop the present waste disposal techniques by doing more economical and feasible due to the increasing environmental concerns and economic pressure (Rajamma *et al*. 2015, Vu *et al.* 2019).

Cement production needs enormous energy consumption and is responsible for approx.7 % of total greenhouse gas emissions in the world (Malhotra 2002). Fly ash (FA) is a by-product of pulverized coal-burning electric power plants. More than 500 million tons of coal-fired fly ash are produced annually in thermal power plants all over the world. Only 25 % - 30 % of this fly ash can be reused in different sectors (Xu and Shi 2018, Mathapati *et al.* 2022). Fly ash has a surface area ranging from 300 m^2/kg to 500 m^2/kg and a bulk density ranging from 0,54 g/cm^3 to 0,86 g/cm^3. It contains large amounts of spherical shaped particles ranging from 10 µm to 50 µm and a small amount of irregularly shaped particles (Sanalkumar *et al.* 2019, Mathapati *et al.* 2022). It is a pozzolanic material reacting with calcium hydroxide to form calcium silicate hydrate gel. Saha (2018) investigated the effect of fly ash on the durability of concrete, and the results showed that the use of fly ash as a partial replacement for cement reduced the drying shrinkage of concrete, and increased the long-term compressive strength. Saboo *et al.* (2019) concluded that the use of fly ash over 20 % based on cement weight caused a decrease in the mechanical properties of concrete. Zhang *et al.* (2021) researched the effect of fly ash replacement ratio on fiber- reinforced cementitious composites. It was found out that the use of fly ash up to 25 % led to an improvement in the workability of the composites and the better fiber dispersion in cement matrix, and a marked increase in the strength properties of the composites due to the fly ash's reactivity and packing effect. It was also stated that the excess use of fly ash over 25 % caused a dilution effect, resulting in a decrease in mechanical properties of cementitious composites. Behl *et al*. (2022) stated that the water amount required to produce cement-bonded composites decreased with increasing fly ash content. Golewski (2021) evaluated effect of fly ash content in the reduction of microcracks in Cementous composites and the results showed that the use of 20 % fly ash as partial cement replacement reduced the width of microcracks by more than 40 % compared to fly ash-free concrete. Lin *et al.* (2017) reported that the addition of fly ash at high dosage caused the fly ash to act as an inert filler instead of binder, which led to a decrease in the durability of cement-based composites. Besides enhancing the durability of cement-bonded wood particleboards, the utilization of FA as a partial replacement for cement can provide energy saving. Another benefit of FA is that it can help to minimize the environmental problems by reducing the carbon dioxide emission of cement manufacturing (Yu and Ye 2013, Bui *et al*. 2018). In addition, the effective utilization of fly ash in the wood cement board industry can contribute to reducing cement consumption and eliminating waste disposal costs.

The decrease of wood raw materials together with the increasing demand for them, the need to protect nature and economic reasons have made it necessary to use trees more efficiently. The use of wood wastes such as sawdust, mill residues, planer shavings in the manufacturing of wood-based composites has been considered environmentally sustainable, economically viable and socially acceptable (Hays *et al*. 2005).

This work was performed to evaluate the effects of fly ash on the cement-bonded wood particleboards (CBWPs) and to produce more environmentally friendly and economical cement-bonded wood particleboards using fly ash as a partial replacement of cement and spruce (*Picea orientalis*) planer shavings.

MATERIALS AND METHODS

Materials

The woody material used in this work was spruce (*Picea orientalis* (L.) Link.) planer shavings obtained from Artvin Coruh University Furniture and Decoration Atelier in Artvin, Turkey. The planer shavings were chipped into smaller pieces using a knife-ring chipping machine and then screened to remove the dust and the oversized particles. To obtain the high particle surface area and to produce the boards with smooth surface, the fine particles remaining on the 1,5 mm sieve and passing through the 3 mm sieve were utilized for producing of CBWPs. As a cement setting accelerator, calcium chloride ($CaCl_2$) solution was used in order to enhance the compatibility of wood with cement and accelerate the cement hydration reaction. The ordinary Portland cement, manufactured by Askale Cement Co. and the fly ash supplied by ARES Cement Co. (Seyitomer Thermal Power Plant) in Kutahya, Turkey were used in this work as a binding materials. Chemical properties of the ordinary Portland cement and Seyitomer FA were compared in Table 1.

Table 1: Chemical composition and physical properties of the ordinary Portland cement and Seyitomer fly ash.

Chemical composition		
Parameters	32,5 R type Portland cement (% wt.)	Fly ash (% wt.) [Turker *et al*. 2009]
SiO_2	16,87	54,49
Al_2O_3	4,35	20,58
Fe_2O_3	3,02	9,27
SiO_2+ Al_2O_3+Fe_2O_3	-	84,34
CaO	56,39	4,26
MgO	1,97	4,48
SO_3	2,39	0,52
K_2O	0,63	2,01
Na_2O	0,22	0,65
Loss on ignition	13,61	3,01
Physical properties		
Specific gravity (g/cm^3)	2,91	2,13
Particle size (µm)	6,5-90	1-30
Specific surface area (cm^2/g)	4801	2369

Manufacture of CBWPs

All the CBWPs were produced at a constant wood/cement ratio of 1:3. $CaCl_2$ solution at a dosage of 5 % by the cement weight was added to the cement-wood-water mixture. The amount of water required for producing the boards was calculated by means of the equation (1) below, which was formulated by Simatupang (1979) as

$$W_t = 0{,}35C + (0{,}30 - MC)W \qquad (1)$$

where, W_t was water weight (kg), C was weight of cement (kg), MC was spruce planer shavings moisture content (oven-dry basis, %), and W was oven-dry spruce planer shavings weight (kg). The fly ash was applied at 5 %, 10 %, 15 %, and 20 %, based on cement weight, as cement replacement. The manufacturing planning of the experimental cement-bonded wood particleboards was summarized in Table 2.

Table 2: Experimental design for manufacture of CBWPs.

Board Type	Fly ash (%)	Portland cement (%)
F0 (control)	0	100
F5	5	95
F10	10	90
F15	15	85
F20	20	80

The mixture of planer shavings, cement, fly ash, distilled water and $CaCl_2$ solution were uniformly blended and then hand-formed on an aluminium plate inside a wooden mould. Afterwards, the mats were kept under a pressure of 20 kg/cm^2 using a single-layer hot press for 24 h. A temperature of 60 °C was applied on the mats during the first 8 h of the pressing time because it was found that the best mechanical and physical properties were achieved at a pressing temperature of 60 °C in manufacturing cement-bonded wood particleboards from spruce wood (Yel *et al.* 2020).

Four replications were made for each variable studied, totalling 15 single-layer CBWPs with a dimension of 500 x 500 x 10 mm^3 and a target density of 1200 kg/cm^3. After 24 h, the CBWPs were kept in a controlled room at 65 % relative humidity of and 20 °C temperature o for 30 days in order to let the cement to cure. The conditioned boards were processed into test samples for determining physical, mechanical, thermal, and morphological properties.

Determination of physical and mechanical properties

The mechanical performances of CBWPs including modulus of rupture (MOR), modulus of elasticity (MOE), screw withdrawal strength (SW), internal bond (IB) strength were tested in according to TS EN 310 (1999), TS EN 319 (1999), TS EN 320 (2011) standards, respectively. Moreover, physical tests such as density (D), moisture content (MC), water absorption (WA) and thickness swelling (TS) were carried out in accordance with TS EN 323 (1999), TS EN 322 (1999), ASTM D1037 (2006), TS EN 317 (1999) standards, respectively.

Thermogravimetric analysis (TGA/DTG)

The samples were grounded and screened prior to the thermal test. Thermogravimetric analysis-derivative thermogravimetry (TGA/DTG) of the samples were performed by heating of specimens in nitrogen atmosphere up to 900 °C at a heating rate of 10 °C/min in a PerkinElmer STA 6000 Thermal Analyser.

Scanning electron microscope (SEM)

The small fractured samples were dried at 60 °C ± 2 °C until they reached a constant weight before SEM observations. After the fractured samples were coated with gold for 120 seconds, the morphology of the fractured surfaces of the samples was characterized using a scanning electron microscope ZEISS EVO LS 10.

Statistical analysis

The results of mechanical and physical tests were submitted to analysis of variance (One-Way ANOVA) using SPSS 19.0 package software. A comparison of the mean values was done by Duncan’s multiply range test when the differences between the means of board groups were found to be significant ($p < 0,05$).

RESULTS AND DISCUSSION

Physical properties

The means, standard deviations and statistical comparisons of D, MC, TS and WA values of CBWPs containing various amounts of the fly ash (FA) were illustrated in Table 3. Density (D) values of the CBWPs were found to be the highest in the control (F0) and decreased as the usage of the FA increased. This can be interpreted by the fact that the specific gravity of Seyitomer FA (2,13 g/cm^3) used as cement replacement is far less than the Portland cement (2,91 g/cm^3). Zhang *et al.* (2021) reported that an increase in fly ash content led to a significant reduction in the density of fiber-reinforced cement composites due to the lower density of fly ash compared to cement. On the other hand, the study conducted by Saha (2018) indicated that the early age strength of cementitious composites decreased with an increase in fly ash content as the hydration reaction of fly ash takes longer time compared to cement. Therefore, another reason for the decrease in the CBWPs may have been a springback occurred in the fly ash-added CBWPs after the pressing process because the FA decreased the early age strength of CBWPs. This low density can provide some advantages for the CBWPs in terms of transportation and insulation.

Table 3: Physical properties of CBWPs.

Board type	D (g/cm^3)	MC (%)	TS (%)		WA (%)	
			2 h	24 h	2 h	24 h
F0	$1,26^{A}$ ± 0,023	$7,90^{A}$ ± 0,05	$3,86^{A}$ ± 0,23	$5,10^{A}$ ± 0,42	$15,40^{a}$ ± 0,91	$18,53^{A}$ ± 0,64
F5	$1,25^{A}$ ± 0,017	$8,51^{B}$ ± 0,39	$3,73^{A}$ ± 0,40	$4,63^{A}$ ± 0,41	$15,64^{A}$ ± 0,88	$20,06^{B}$ ± 0,53
F10	$1,21^{B}$ ± 0,015	$8,04^{A}$ ± 0,13	$3,34^{A}$ ± 0,32	$4,64^{A}$ ± 0,43	$15,83^{AB}$ ±1,06	$20,20^{B}$ ± 0,65
F15	$1,17^{C}$ ± 0,027	$8,38^{B}$ ± 0,25	$3,16^{A}$ ± 0,26	$4,60^{A}$ ± 0,32	$16,97^{BC}$ ±1,41	$22,25^{C}$ ± 1,23
F20	$1,14^{D}$ ± 0,022	$8,10^{A}$ ± 0,20	$3,39^{A}$ ± 0,23	$4,62^{A}$ ± 0,46	$17,56^{C}$ ± 1,53	$22,77^{C}$ ± 0,68

*Means within a column followed by the different capital letters are significantly difference at 5 % level of significance for Pvalues <0,05. ± represents the standard deviations.

Although the FA had not a statistically significant effect on TS of the CBWPs for both 2 h and 24 h water soaking, it slightly decreased the TS values. This indicated that the C-S-H gel, formed as a result of the FA reaction with $Ca(OH)_2$, contributed to the durability of the CBWPs, despite the reducing content of cement in the binder due to the FA replacement.

On the contrary to the thickness swelling values, as the rate of the FA in the CBWPs increased, a significant increase in water absorption values was observed. This might be caused by the high water holding capacity of FA due to its porous structure (Fischer *et al.* 1978). Ma *et al.* (1995) reported the surface area of FA, after reacting with $Ca(OH)_2$, dramatically increased due to C-S-H gel with a huge surface area, and as a result of this, the volumes of pores increased. A study conducted by Karahan (2006) on the utilization of FA as cement replacement up to 45 % in producing the polypropylene and steel fibre reinforced concretes indicated that the porosity and water uptake rates of concrete increased as the utilization of FA increased. Tkaczewska and Małolepszy (2009) also stated that the porosity of the cement-based composite increased as FA replaced cement. In addition, the increment in the water absorption values of the CBWPs with fly ash added is thought to be associated with the decrease in the density of the CBWPs. Ashori *et al.* (2012) concluded that the wood cement panels with low density have more void spaces than the dense ones. Therefore, they can uptake more water.

MC values of all the CBWPs were found incompatible with the MC requirement (6 % - 12 %) mentioned in TS EN 634-1 (1999) standard. However, none of the CBWPs met the maximum thickness swelling requirements (<1,5 %) in the same standard.

Mechanical properties

The means, standard deviations and statistical comparisons of MOR, MOE, IB, SW values of CBWPs containing various amounts of fly ash were given in Table 4. The values of modules of rupture and modules of elasticity ranged from 9,18 MPa to 11,71 MPa and from 5096 MPa to 6175 MPa, respectively and all of them were well above the minimum MOR (9 MPa) and MOE (4000 MPa) requirements set forth by TS EN 634-2 (2007) standards for ordinary Portland cement (OPC) bonded particleboards. The main products of hydration reaction of cement are calcium silicate hydrate (C-S-H) gel, which is primarily responsible for the mechanical performance of CBWPs and calcium hydroxide [$Ca(OH)_2$], which has no contribution to the mechanical properties. The FA reacted with $Ca(OH)_2$ to form more C-S-H gel. Therefore, the FA improved the MOR and MOE values of the CBWPs because the CBWPs containing the FA had more C-S-H than that in the control. In addition to the pozzolanic reactivity of fly ash, its smaller particle size and lower specific gravity compared to cement may have contributed to the improvement in MOR and MOE of CBWPs.

It was seen that the highest MOR and MOE values were achieved in the CBWPs containing 5 % the FA and the the MOR and MOE values decreased as the use of the FA increased over 5

%. The reason for this may be that the amount of cement decreases as the FA usage rate increases, and as a result, not all the FA particles could react with calcium hydroxide since the amount of calcium hydroxide reduced due to the decrease in the amount of cement used. Consequently, the excess FA acted as an inert filler instead of binder, resulting in a reduction in the mechanical properties of the CBWPs (Lin *et al.* 2017).

Table 4: Mechanical properties of the CBWPs.

Board Type	MOR (MPa)	MOE (MPa)	IB (MPa)	SW (N/mm)
F0	$9,18^{C}$ ± 0,51	5506^{C} ± 294	$1,13^{A}$ ± 0,11	$97,46^{A}$ ± 8,54
F5	$11,71^{A}$ ± 0,74	6175^{A} ± 261	$0,83^{B}$ ± 0,08	$93,94^{AB}$ ± 8,31
F10	$11,08^{B}$ ± 0,38	5875^{B} ±182	$0,83^{B}$ ± 0,06	$91,06^{AB}$ ±6,82
F15	$10,93^{B}$ ± 0,56	5581^{C} ± 258	$0,78^{B}$ ± 0,07	$91,17^{AB}$ ± 7,09
F20	$10,51^{B}$ ± 0,70	5096^{D} ± 368	$0,77^{B}$ ± 0,05	$86,70^{B}$ ± 4,36
* Means within a column followed by the different capital letters are significantly difference at 5 % level of significance for Pvalues <0,05. ± represents the standard deviations.				

Saboo *et al.* (2019) concluded that the use of fly ash at high dosage caused a decrease in the mechanical properties of concrete. Zhang *et al.* (2021) also stated that utilization of fly ash at low dosage led to a significant increase in the strength properties of the fiber-added cement composites due to the fly ash's reactivity and packing effect, whereas fly ash at high dosage caused a dilution effect. In addition, the reduction in the boards' density with the increase of the fly ash content may have contributed to the decrease in the MOR and MOE of the boards.

It was observed that all the CBWPs containing the FA had a higher MOR value than the control. On the other hand, the difference between the MOR values of the CBWPs (F10, F15, F20) containing 10 %, 15 % and 20 % FA was statistically not significant in according to the results of the ANOVA test. Some researchers (Saha 2018, Saboo *et al.* 2019, Al-sallami *et al.* 2020; Venkateswara and Srinivasa 2020) stated that the addition of FA at the low dosages significantly improved the mechanical properties of cementitious composites due to its pozzolanic activity. Furthermore, Horsakulthai and Paopongpaiboon (2013) mentioned that fly ash (FA) concrete with bagasse-rice husk-wood ash (BRWA) additive improved in strength, compared to Portland cement concrete, due to the fact that both BRWA and FA reacted with $Ca(OH)_2$ to produce more C-S-H gel.

The IB and SW values ranged from 0,77 MPa to 1,13 MPa and 86,70 MPa to 97,46 MPa, respectively. The highest IB and SW values were achieved in the control. It was observed that the IB and SW values slightly decreased with an increase in fly ash content. This may have been due to the fact that fly ash caused the springback and low density in the CBWPs. However, the IB values of all the CBWPs exceeded the minimum IB requirement (0,5 MPa) stipulated in TS EN 634-2 (2007) standard. In addition, the difference between the IB values of all the CBWPs containing the FA was statistically not significant.

Thermal properties

TGA-DTG curves of the CBWPs made at different cement replacement levels with the fly ash (FA) were shown in Figure 1. The first peak represented the dehydration of pore water (approx. 100 ºC) in the CBWPs. The second peak indicated the decomposition of wood components [hemicellulose (180°C to 350 °C), cellulose (275 °C to 350 °C) and lignin (250 °C to 500 °C)] (Kim *et al.* 2006).

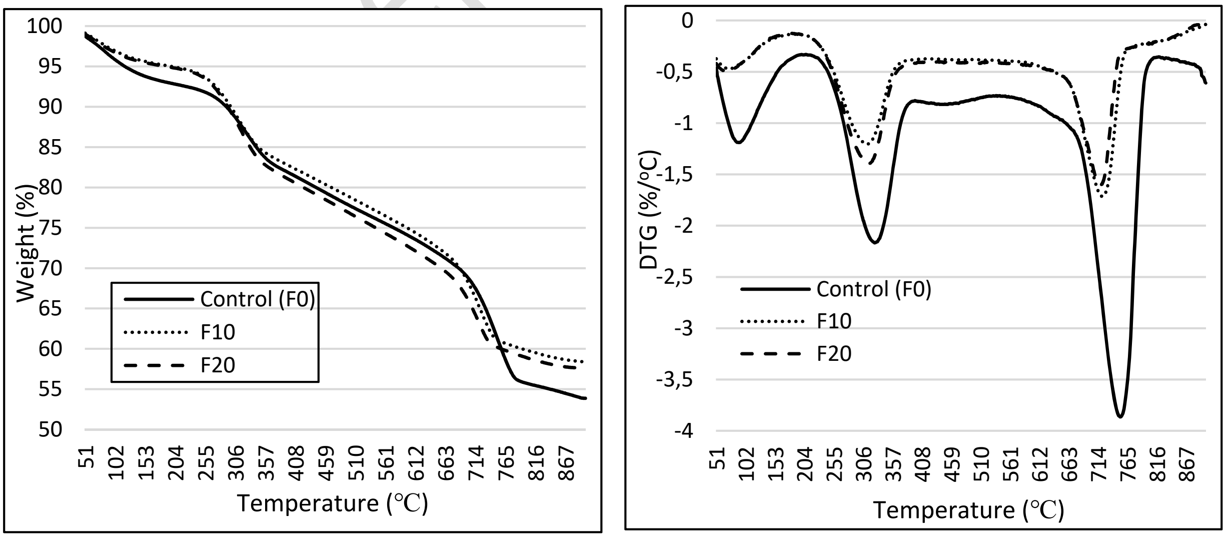

Figure 1: TGA/DTG curves of CBWPs containing FA.

The third peak slightly occurred at about 450 °C due to the decomposition of calcium hydroxide [$Ca(OH)_2$]. The reason why calcium hydroxide decomposition occurred very slightly may have been due to the fact that the pozzolanic reaction of the FA consumed calcium hydroxide [$Ca(OH)_2$], which formed as a result of cement hydration reaction, in the CBWPs. In addition, another reason could be said to be the carbonation reaction, a reaction of calcium hydroxide [$Ca(OH)_2$] with carbon dioxide (CO_2), because the peaks between 700 °C - 800 °C were quite high. The last peak, occurred at approx. 750 °C, showed the decarbonisation of calcium carbonate ($CaCO_3$) which is not a product of cement hydration process such as ettringite, C-S-H, monosulphate and $Ca(OH)_2$. The FA significantly reduced the calcium carbonate ($CaCO_3$) in the CBWPs, compared to the control. This demonstrated that there was not enough calcium hydroxide for the carbonation reaction in the CBWPs because of the pozzolanic reaction of the FA with calcium hydroxide [$Ca(OH)_2$].

Morphological properties

Micrographs of fractured surfaces of the CBWPs with the FA were shown in Fig. 2. The formations of C-S-H, ettringite, and $Ca(OH)_2$, which resulted from the cement hydration reaction, were observed in the SEM views of the CBWPs. It is believed that there is a mechanical interlocking process between C-S-H gel and the rough wood surface and this makes a very important contribution to the strength of the wood-cement composites (Hermawan *et al.* 2001).

As the usage of the FA increased in the CBWPs, it was seen that the amount of C-S-H gel significantly increased, whereas the content of $Ca(OH)_2$ decreased. This explains why the FA improved the flexural and thickness swelling properties of the CBWPs. Moreover, it was seen that the FA increased the size and number of voids in the CBWPs. This may have been one of the reasons for the increase in the water absorption of the CBWPs.

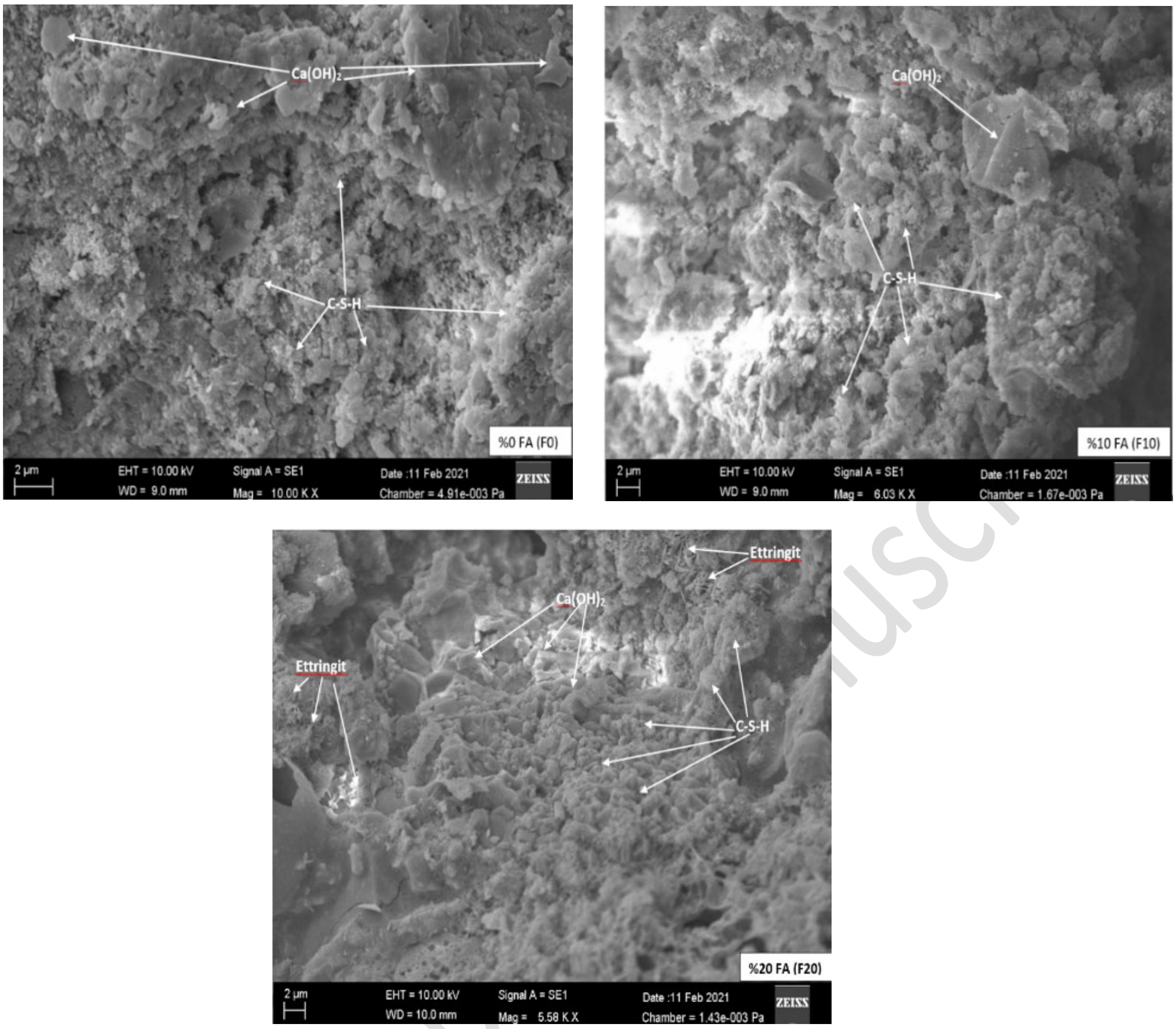

Figure 2: SEM images of fractured surfaces of the CBWPs with the FA.

CONCLUSIONS

The usage potential of the fly ash (FA) as a partial cement replacement in manufacturing cement-bonded wood particleboards was investigated in this paper. According to the findings of this work, the following conclusions can be drawn:

1. The results demonstrated that it is possible to manufacture more environmentally friendly and durable cement-bonded wood particleboards using the FA as partial cement replacement and spruce planner shavings as virgin wood particles replacement. In addition, the cement-bonded wood particleboards in this study are considered to be more

economical than traditional cement-bonded wood particleboards because they were produced using waste materials in this study.

2. The highest MOR and MOE values were achieved in the CBWPs containing 5 % FA, and as the use of FA increased over 5 %, the MOR and MOE values of the CBWPs decreased. Moreover, the FA negatively affected the IB and SW values of CBWPs. MOR, MOE, IB values of all the CBWPs met the requirements mentioned in the standards. By using the FA up to 20 % as cement replacement and 100 % spruce planer shavings, cement-bonded wood particleboards with mechanical properties above the required level of the standards could be produced.

3. The FA decreased the density values of the CBWPs due to the lower density of the FA compared to cement and the springback occurred in the fly ash-added boards. The FA improved the thickness swelling values thanks to the increasing C-S-H gel as a result of the reaction of the FA with $Ca(OH)_2$. However, the FA increased the water absorption values due to its high water holding capacity and porosity. In addition, the decrease in the density of the fly ash-added boards resulted in an increase in the water absorption values of the boards.

4. In TGA/DTG of CBWPs, less weight losses occurred in 400 ºC - 500 ºC and 700 ºC - 800 ºC because the FA decreased the amount of $CaCO_3$ and $Ca(OH)_2$ by reacting with $Ca(OH)_2$.
5. It was observed that the FA increased C-S-H gel and decreased $Ca(OH)_2$ in cement-bonded wood particleboards.

6. Additional works are required to determine the effects of FA on cement-bonded wood particleboards produced using different tree species, cement setting accelerator and cement types.

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