Hybrid Composite Board Produced from Wood and Mineral Stone Wool Fibers

Memiş Akkuş *

Wood fiberboards are used extensively, mainly in the fields of furniture production, interior fittings, construction, *etc.* Mineral stone wool materials are used for heat and sound insulation in the construction industry. This study aimed to produce a new hybrid-based composite material by mixing fibers obtained from wood and mineral stone wool. For this purpose, hybrid fiberboards with 50, 40, 30, and 20% stone wool addition and a fiberboard group consisting of 100% pine and beech fibers (control sample) were produced in a hot press using thermoset-based urea formaldehyde and phenol formaldehyde resins. Statistical comparisons of the results were made for values of density, thickness swelling, and water absorption extents after 24 h immersion, bending strength and modulus of elasticity in bending, tensile strength perpendicular to the board surface (internal bond strength), and time to ignition (TTI) analysis. Additionally, percentage of mass loss (PML), average heat release rate (A-HRR), average effective heat of combustion (A-EHC), and mass loss rate (MLR) were studied. The results showed that as the stone wool content in the produced boards increased, the mechanical properties and thickness swelling decreased. The combustion results showed that the combustion resistance of the boards increased with increasing stone wool ratio.

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*Contact information: Faculty of Architecture and Design, Industrial Products Design, Konya Technical University, Selçuklu, 42130, Konya, Türkiye; *Corresponding author: memisakkus@duzce.edu.tr*

INTRODUCTION

The fiberboard construction market is rapidly expanding and the products are used under extreme conditions. Fire retardant-treated fiberboards are increasingly used in exteriors for both roofing and building cladding. Production has begun of fire retardant-treated molded wall panels for use as both cladding and structural composite materials (Ayrilmis 2007). Many chemical compounds are used as flame retardants in lignocellulosic-based boards (Kozlowski *et al.* 1999). Boron compounds applied as a fire retardant at the levels of 5, 10, and 15% adversely affected water absorption, thickness swelling, bending strength, and internal bond strength values of medium-density fiberboard (MDF) panels produced using melamine-urea formaldehyde (MUF) resin (Ustaomer and Usta 2012). The combustion, physical, and mechanical properties of fiberboards produced using polyphosphate-based fire retardant were examined in a laboratory environment. Results showed that critical flame resistant (FR) parameters, such as peak heat release rate (peak HRR), total heat release (THR), and total smoke production (TSP) values, were improved; however, internal bond strength, thickness swelling, and water absorption rates were negatively affected (Mantanis *et al.* 2019). The effects on the FR properties of 10, 15, and 20 g/kg wollastonite nanofibers in MDF boards were investigated, and results showed that with the increase of the wollastonite nanofiber ratio, combustion parameters, such as weight loss, ignition and flash point time, and flame resistance, were significantly improved (Taghiyari *et al.* 2013). Esmailpour *et al.* (2021) reported that the combustion properties of MDF boards produced from urea formaldehyde (UF) resin with camel-thorn as a filler and nano-wollastonite (NW) as an additive were improved with increasing NW proportion. Aluminum hydroxide and borate chemical compounds together with ammonium polyphosphate (APP) were used in MDF production and the technological, and combustion properties of the boards were investigated. Results determined that the chemical compounds improved the water absorption and thickness swelling values and increased the fire resistance of the boards; however, they reduced the internal bond strength 48% (Martinka *et al.* 2021). Ustaomer and Başer (2020) investigated the combustion and thermal properties of MDF boards produced using mineral-based chemicals containing huntite/hydromagnesite and zinc borate (ZB) at different concentrations. According to the results, all mineral-based chemicals significantly affected the limiting oxygen index (LOI) and thermogravimetric analysis values.

Stone wool is an insulation material that contains natural fiber obtained by transforming minerals and inorganic volcanic stone into natural fiber by melting at 1600 °C. Stone wool performs heat insulation, sound insulation, damp insulation, and fire protection quite efficiently in applications including roofing of houses, partition walls, exterior walls, ovens, steel doors, boats, domestic appliances, and entertainment venues like cinemas and theaters (Ravaber 2020). In general, one of the important advantages of inorganic materials such as stone wool is that they can be used at high temperatures of up to 1000 °C. Thus, they are found in a wide variety of usage areas that have fire protection requirements and high fire-resistance standards. As a result of their research on hemp fiber, cellulose fiber, and mineral stone wool as thermal insulation materials, Kosiński *et al.* (2020) reported that mineral stone wool exhibited a strong hydrophobic property and had the highest contact angle. However, water infiltration into inorganic fibrous materials affects their properties. Therefore, the condensation that occurs in the material is of great importance in determining the stone wool performance (Karamanos *et al.* 2008). Ülker and Burdurlu (2015) produced particleboards with UMF resins and different additions (10, 15, and 20%) of glass wool and stone wool and investigated the combustion properties of the boards according to DIN 4102 (1998) standard. According to the results, they stated that the adhesive type did not affect the ignition time or mass loss values and that the combustion properties of the particleboards were improved with increases in the glass wool and stone wool ratios. It was reported that in biocomposite materials produced using 20, 30, and 40% stone wool in polylactic acid (PLA), the bending strength value decreased 5 to 40% and the tensile strength by 40 to 60% with the increase of the stone wool ratio (Aykanat and Ermeydan 2020). Jetsu *et al.* (2020) used wood and mineral wool from demolished buildings formed in appropriate sizes in the production of wood-plastic composite materials. They reported that because the mechanical properties of these materials were at a good level, they could be used in wood-plastic composites of the type widely used in flooring applications. As a result of examining the mechanical properties of particleboards produced using glass wool and stone wool, Ülker and Burdurlu (2016) reported that the glass wool and stone wool reduced the bending strength and modulus of elasticity of the board 49%, shear strength by 8%, screw tensile strength by 3%, and tensile strength by 6%. Mamiński *et al.* (2011) investigated the thickness swelling and mechanical and thermal properties of particleboards produced by adding mineral wool at the rates of

10, 20, and 30% using UF resin as a binder. According to their results, depending on the increase in mineral wool, the mechanical properties and thermal conductivity values decreased and the thickness swelling increased. Existing studies have generally shown a reasonable increase in the ignition and combustion resistance of wood-based composite materials mixed with stone wool fillers; however, the deterioration of mechanical properties cannot be disregarded for wood – polypropylene composites (Yap *et al.* 2021). Recently, the interest in and demand for environmentally friendly engineered wood-based products has been increasing as a result of the energy crisis and health concerns. In addition, the use of environmentally friendly wood-based composite boards is of great importance because the heat and toxic contents of structure fires cause them to grow and spread toxic smoke (Badel *et al.* 2008; Huang *et al.* 2017).

This study aimed to use environmentally friendly mineral stone wool fibers instead of fire retardant chemical compounds in the production of wood-based fiberboard, thus enabling the production of a new hybrid-based fiberboard. These hybrid-based fiberboards were produced by adding urea formaldehyde and phenol formaldehyde resins to 100% wood fiber (control) and to wood fiber with additions of 20, 30, 40, and 50% bulk stone wool fiber (loose, without binder). The density, water absorption, thickness swelling, internal bond strength, bending strength, modulus of elasticity, and combustion properties were then investigated.

EXPERIMENTAL

Materials

Beech and pine wood fiber was procured from Kastamonu Entegre Ağaç Sanayi A.Ş. in Gebze/ Kocaeli (Turkey) and cast stone wool (without binder) from Ravaber Yapı Ürünleri San. Tic. A.Ş. operating in Kayseri (Turkey). Technical specifications of the cast stone wool are given in Table 1. Stone wool fibres has not been subjected to any treatment such as binder or impregnation. Pure loose stone wool fibres were used in the production. The phenol formaldehyde glue was obtained from ASD laminate company in Düzce (Turkey) and the urea formaldehyde glue from Divapan A.Ş, also in Düzce (Turkey). The technical properties of the urea formaldehyde and phenol formaldehyde glues are given in Table 2.

Table 1. Stone Wool Technical Specifications

Product Name	Loose Stone Wool		
Standard	TS EN 13162+A1 (2015)		
Description	Mineral wool - Thermal insulation material for thermal, sound, and fire insulation - Formed by melting basalt stone into fiber at 1350 to 1400 °C		
Areas of Usage	Used as heat and sound insulation and for fire safety		
Properties	**Unit**	**Value**	**Standard**
Density	Kg/m^3	Max. 80	TS EN 1602 (2013)
Reaction to Fire	-	A1	TS EN 13501-1 (2019)
Thermal Conductivity (10 °C)	W/mK	Max. 0.035	TS EN 12667 (2003)
Max. Operating Temperature	°C	760	-
Melting Point	°C	> 1000	DIN 4102 (1998)
Approximate nominal diameter of the fibers	μm	3.5 – 4.5	

Table 2. Technical Properties of Glues Used in Boards Production

Properties	Urea Formaldehyde	Phenol Formaldehyde
Appearance	White	Orange
Solid Matter (%)	55	59.8
Density (g/cm^3)	1.240	1.152
pH at 20 °C	8	8.3
Gel Time at 100 °C	35	9.2
Viscosity (s)	32.5	17.27

Methods

Wood fibers were taken from the factory in full wet state and were oven-dried at 80 °C until 2 to 3% humidity was reached. To separate the clumped stone wool fibers to be used in production, the wool was passed through a carding machine (Fig. 1).

Fig. 1. Separation of stone wool into fibers in a wool carding machine

Fig. 2. a) The appearance of stone wool fiber and wood fiber **b)** Mixing of stone wool fiber and wood fiber

As indicated in Table 3, mixtures of wood fibers and 20, 30, 40, and 50% stone wool fiber were used (Fig. 2), with 100% wood fiber as the control group. As binders, urea formaldehyde and phenol formaldehyde glues at up to 12% of the dry fiber weight were used in the blends. Together with the urea formaldehyde glue, 1% (of glue weight) ammonium sulfate hardener was used.

Pressing conditions used for the urea formaldehyde resin were 50 bar at 165 °C for 7 min, whereas for the phenol formaldehyde resin, 50 bar pressure was used at 190 °C for 12 min (Fig. 3). A total of 10 groups of 420 × 420 × 12 mm^3 samples were obtained, consisting of five groups with urea formaldehyde and five groups with phenol formaldehyde (Fig. 4). The experimental design for the study is presented in Table 3.

Fig. 3. a) Laying, pre-pressing **b)** Hot pressing of blended fibers in the mold

Fig. 4. Hybrid fiberboard samples produced from a mixture of stone wool fiber and wood fiber

The samples used to test the bending strength and modulus of elasticity, density, water absorption, thickness swelling, and bond strength were placed in an air-conditioning cabinet under conditions of 65% relative humidity and 20 °C until they reached a stable weight. Combustion samples were conditioned at 20 °C and 50% relative humidity until their weight became stable. For the density test, a total of 80 samples (8 from each group) were prepared according to TS EN 323 (1999) standard in dimensions of 500 × 500 mm^2. For the thickness swelling/water absorption tests, a total of 80 samples (8 from each group) were prepared according to TS EN 317 (1999) standard in dimensions of 500 × 500 mm^2. The initial thickness (t_1) of the prepared samples and the final thickness (t_2) after removal from the 24-h water soak were measured and the thickness swelling ratio was calculated using the formula TS = ((t_2 - t_1) /t_1) × 100. The water absorption extent was determined according to ASTM D1037-12 (2020) standard. The initial weights (w_1) of the prepared samples and the final weights (w_2) after removal from the 24-h water soak were measured, and the water absorption was calculated using the formula WA = ((w_2 - w_1) /w_1) × 100 (Fig. 5). For bending strength and flexural modulus of elasticity, a total of 80 samples (8 from each group) in dimensions of 280 × 50 × 12 mm^3, were prepared and tested according to the TS EN 310 (1999) standard. For the bond strength, a total of 60 samples (6 from each group) in dimensions of 50 × 50 mm^2 were tested according to the TS EN 319 (1999) standard.

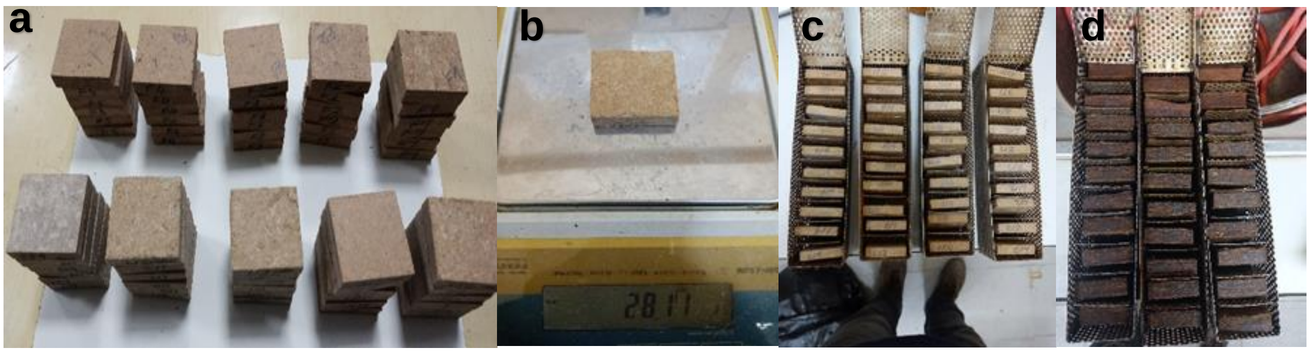

Fig. 5. a) Test samples **b)** The weighing of test samples **c)** The putting of test samples in the wireframe **d)** Test samples after water soaking

A mass loss calorimeter (MLC) (FTT Fire Testing Technology Ltd., London, United Kingdom) was used for the combustion analysis (Fig. 6). For this analysis, a total of 30 samples (3 from each group) in dimensions of 100 × 100 × 10 mm^3 were tested according to the ISO 13927 (2001) standard. The samples were tested at a heat flux level of 50 kW/m^2 and a constant temperature of 724 °C. During combustion, the time-dependent weight loss data, ignition time, heat release rate, and effective combustion heat of the samples were recorded by the computer. The data were statistically analyzed *via* SPSS statistical software (version 21.0, SPSS Inc., Chicago, IL, USA) using analysis of variance (ANOVA) and Duncan's mean separation test ($p < 0.05$).

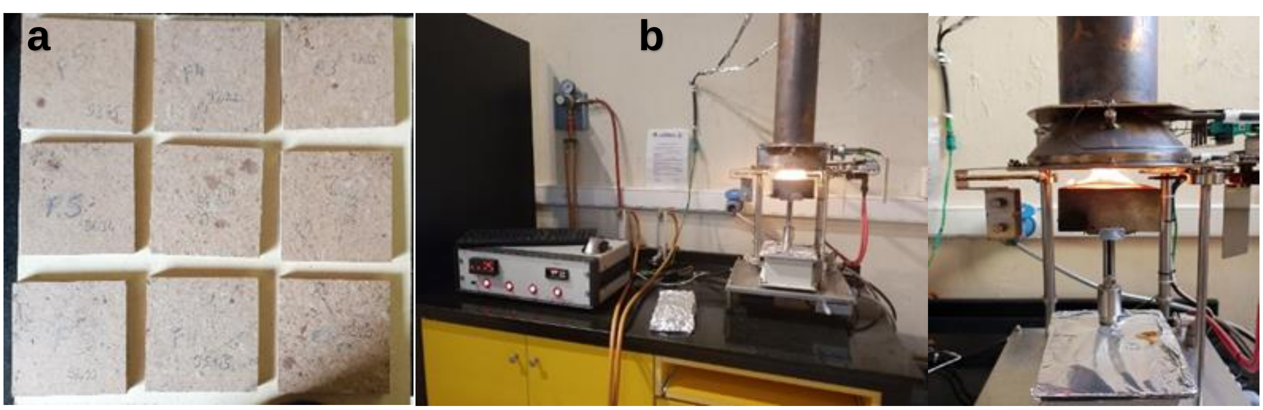

Fig. 6. a) Combustion test samples **b)** The experiment in a cone calorimeter

Table 3. Experimental Design of the Study

Code	Wood Fiber (%)	Stone Wool Fiber (%)	Urea Formaldehyde (%)	Phenol Formaldehyde (%)	Performance Tests
UC	100	0	12	-	• Bending Strength • Modulus of Elasticity • Water Absorption • Thickness Swelling • Bond Strength • Combustion Analysis
U1	80	20	12	-	
U2	70	30	12	-	
U3	60	40	12	-	
U4	50	50	12	-	
FC	100	0	-	12	
F1	80	20	-	12	
F2	70	30	-	12	
F3	60	40	-	12	
F4	50	50	-	12	

RESULTS AND DISCUSSION

Mechanical and Physical Properties

Table 4 shows the statistical comparison of the density, bending strength (modulus of rupture), modulus of elasticity, internal bond strength, water absorption, and thickness swelling of the composite boards obtained from the mixtures of cast stone wool fiber and wood fiber.

Table 4. Comparison of the Mechanical and Physical Values of the Hybrid Composite Boards

Code	Density (kg/m^3)	Modulus of Rupture (N/mm^2)	Modulus of Elasticity (N/mm^2)	Internal Bond Strength (IB) (N/mm^2)	24-h Water Absorption (%)	24-h Thickness Swelling (%)
UC	923 (66.1)[ab]	20.11 (3.01)[b]	**10634 (1353)[a]**	**0.39 (0.04)[a]**	75.95 (7.69)[b]	**40.35 (5.47)[a]**
U1	893 (52.5)[abc]	19.70 (4.74)[bc]	10011 (1110)[a]	0.33 (0.01)[b]	65.54 (7.80)[cd]	21.75 (2.95)[cd]
U2	893 (39.5)[abc]	20.63 (2.09)[b]	10515 (694)[a]	0.28 (0.18)[c]	59.58 (7.90)[de]	17.35 (0.79)[de]
U3	888 (24.6)[abc]	11.49 (0.67)[d]	8499 (642)[b]	1.33 (0.01)[f]	72.73 (5.51)[ab]	25.62 (6.52)[bc]
U4	833 (36.4)[d]	7.95 (1.43)[e]	9807 (1351)[a]	0.05 (0.02)[g]	74.32 (14.35)[b]	18.05 (7.47)[de]
FC	**929 (32.2)[a]**	**30.92 (1.70)[a]**	9607 (591)[a]	**0.41 (0.06)[a]**	**41.62 (3.01)[f]**	14.23 (1.27)[ef]
F1	881 (24.6)[bc]	21.01 (1.69)[b]	8056 (690)[bc]	0.24 (0.01)[d]	56.79 (3.81)[e]	17.11 (8.80)[de]
F2	847 (23.1)[cd]	17.36 (2.47)[c]	7152 (916)[cd]	0.16 (0.007)[e]	62.77 (2.92)[de]	11.77 (1.04)[f]
F3	859 (57.9)[cd]	13.69 (1.61)[d]	6446 (747)[d]	0.11 (0.01)[f]	64.21 (8.34)[de]	**9.90 (0.59)[f]**
F4	**820 (36.4)[d]**	**5.47 (0.53)[f]**	**1922 (199)[e]**	**0.02 (0.005)[h]**	**97.23 (9.66)[a]**	29.47 (5.86)[b]

Values in parentheses are the standard deviations; different letters in the density, modulus of rupture, modulus of elasticity, internal bonding, water absorption, and thickness swelling columns indicate statistical differences at the 95% confidence level.

In the hybrid boards produced using urea formaldehyde resin, the highest density value (923 kg/m^3) was obtained in boards using 100% wood fiber, whereas the lowest value (833 kg/m^3) was found in samples using 50% wood fiber and 50% stone wool fiber. No statistical difference was found between the densities of the samples in which urea formaldehyde resin was used with the stone wool fiber at the rates of 20% (893 kg/m^3), 30% (893 kg/m^3), and 40% (888 kg/m^3). In the boards produced using phenol formaldehyde resin, the highest density value (929 kg/m^3) was obtained in the control group boards, whereas the lowest value (820 kg/m^3) was found in the board group in which 50% stone wool (the highest stone wool ratio) was used. There was no statistical difference between the densities of the board groups in which phenol formaldehyde was used with stone wool fiber at rates of 30% (847 kg/m^3) and 40% (859 kg/m^3). Although the press pressure and temperature used were the same, the density of the boards decreased due to the increase in stone wool. This was attributed to the low density of the stone wool fibers and the lower compression ratio (board density/wood density) compared to wood fibers, and to the different solid contents and densities of the resins used. In addition, boards with a high stone wool fiber ratio had more springback after exiting the hot press, and depending on the increase in board thickness, this affected the density. In MDF production, the density depends on the type of wood and resin used, the production parameters, and the compression ratio (Akbulut and Ayrılmış 2001). Moreover, these also have an effect on the density and mechanical and physical properties of wood-based composite boards (Ayrilmis 2007; Li *et al.* 2013).

The highest modulus of rupture (MOR), *i.e.*, bending strength value (30.92 N/mm^2), was detected in the FC samples using 100% wood fiber, whereas the lowest (5.47 N/mm^2) was obtained in the F4 samples using 50% stone wool fiber. There was no sudden decrease in bending strength because the increase in stone wool fiber was determined in the samples using urea formaldehyde glue. The UC (20.11 N/mm^2), U1 (19.70 N/mm^2), and U2 (20.63 N/mm^2) board samples gave similar results in terms of bending strength values. However, the bending strength value decreased significantly with the addition of stone wool fiber in the boards produced with phenol formaldehyde resin. In terms of bending strength values, there was no statistical difference between the UC (20.11 N/mm^2), U2 (20.63 N/mm^2), and F1 (21.01 N/mm^2) boards and the F3 (13.69 N/mm^2) and U3 (11.49 N/mm^2) boards. There was a decrease in bending strength due to the increased rate of stone wool fiber in the boards. Maminski *et al.* (2011) stated that as a result of using 10%, 20%, and 30% mineral wool in particleboard, the bending strength of the board decreased with the increase in the mineral wool ratio. The highest modulus of elasticity (MOE) value was obtained in the UC (10634 N/mm^2) samples using 100% wood fiber, and the lowest in the F4 (1922 N/mm^2) samples using 50% stone wool fiber. There was no statistical difference in the MOE between the UC (10634 N/mm^2), U1 (10011 N/mm^2), U2 (10515 N/mm^2), U4 (9807 N/mm^2), and the FC (9607 N/mm^2) board groups. Similar results were obtained for the MOE of the hybrid boards produced using urea formaldehyde resin. However, there was a reduction in the MOE with the increase in stone wool fiber in the groups using phenol formaldehyde resin. Ülker and Burdurlu (2015) reported that as a result of using stone wool and glass wool as fire retardants in wood composite material, regardless of adhesive type or additive ratios, they reduced the bending strength and MOE of the composite board at similar rates (on average by 49%). Wang *et al.* (2016) reported that by using different ratios of vermiculite (V) in MDF production, with the increase of the V/fiber ratio, the bending strength and the MOE in bending of the board rapidly decreased.

Among the hybrid board groups, the highest internal bond value was in the FC board groups (0.41 N/mm^2) and UC (0.39 N/mm^2) groups with 100% wood fiber. The lowest internal bond strength (0.02 N/mm^2) was in the F4 group, in which 50% stone wool fiber was used. However, there was no statistical difference between the UC and FC groups in terms of internal bond strength. It has been reported that in particleboards produced by adding 10, 20, and 30% stone wool using urea formaldehyde glue, the mineral wool reduced the bending strength by up to 65% and the internal bond strength by up to 71%, due to the reduction of the cohesion force inside the board (Mamiński *et al.* 2011; Yap *et al.* 2021). Cong *et al*. (2021) added a layer of mineral wool and glass wool to epoxy-based carbon fiber polymeric laminates and investigated their combustion and mechanical properties. Results indicated that the addition of the flame-retardant layers reduced the bending strength from 836.4 to 767.0 MPa. In wood-plastic composite (WPC) material produced using recycled mineral wool, the bending and tensile properties of the material decreased as a result of the increase in mineral wool content (Väntsi and Kärki 2014). Öztürk (2010) obtained hybrid composite materials from mixtures of jute/phenol formaldehyde, stone wool/phenol formaldehyde, and jute/stone wool/phenol formaldehyde in different ratios. The tensile, bending, and impact strength values of the jute/phenol formaldehyde composite material were higher than for the stone wool/phenol formaldehyde composite material. Özdemir (2019) reported that the use of dolomitic sepiolite and perlite minerals in different proportions in the production of MDF negatively affected the physical and mechanical properties of the board. The use of glass fiber and stone wool in particleboard production, depending on the type of adhesive and additive ratio, reduced the mechanical properties of the boards by 75% from 39% (Ülker and Burdurlu 2016).

The highest water absorption rate of the boards after the 24 h soak in water (97.23%) was determined in the F4 board group in which 50% stone wool was used, and the lowest (41.62%) in the FC samples in which 100% wood fiber was used. No statistical difference was found between the UC (75.95%) and U4 (74.32%) and the U2 (59.58%), F2 (62.77%), and F3 (64.21%) board groups in terms of water absorption rate. The water absorption tests among the board groups produced using urea formaldehyde resin yielded similar results. In the samples using phenol formaldehyde resin, the water absorption values increased as a result of the increase in the stone wool fiber ratio. This may have been caused by the weakening of the binding strength with the increase in the ratio of stone wool used in the hybrid fiberboard. The reduction of the cohesive force in hybrid fiberboard was thought to cause the board to absorb more water into its structure. At the end of 24 h, the highest thickness swelling ratio (40.3%) of the boards removed from the water was found in the UC board group, where 100% wood fiber was used, whereas the lowest (9.9%) was in the F3 board group with 40% stone wool fiber. There was no statistical difference between the F2 (11.77%) and F3 (9.9%) and the U2 (17.35%), U4 (18.05%), and F1 (17.11%) board groups in terms of thickness swelling. In general, as the stone wool ratio increased in the hybrid board, the swelling ratio decreased. This is due to the more hydrophilic nature of the wood fibers than the stone wool fibers. Cracks were observed in the samples that were kept in water for 24 hours. These cracks are due to the fact that it does not form a strong bond between the stone wool fiber and the wood fiber. However, similar cracks occur in wood fiberboards that have been soaked in water for 24 hours. Maminski *et al*. (2011) reported that because of soaking in water for 24 h, the thickness swelling ratio of particleboard samples produced with 10, 20, and 30% stone wool using urea formaldehyde resin increased from 36.1 to 49.1%, depending on the increase in stone wool. Phenol formaldehyde resin is known to be more resistant to outdoor or humid conditions than urea formaldehyde resin. For this reason, despite the high water absorption in the hybrid-based composite boards, the use of phenol formaldehyde resin was effective in the low thickness swelling ratio. Because the hydroxyl groups in the microstructure of cellulose-based fibers have water-binding properties, the absorbed moisture or water causes the fibers to swell. However, due to the more hydrophobic nature of stone wool fibers than wood fibers, thickness swelling is not thought to occur as a result of water absorption. The capacity of mineral wool for absorption of hygroscopic moisture is very low and its water vapour diffusion permeability very high (Antepara and Pavlik 2016). Väntsi and Kärki (2014) reported that as a result of using 20, 30, and 40% mineral wool as a filler in wood-plastic composite material, there was a decrease in the water absorption and thickness swelling rates, depending on the increase in recyclable stone wool. They stated that this was because stone wool does not absorb water into its structure.

Combustion Performance

For the composite boards obtained from mixtures of cast stone wool fiber and wood fiber, Table 5 gives a statistical comparison of time to ignition (TTI), percentage of mass loss (PML), and average heat release rate (A-HRR), average effective heat of combustion (A-EHC), and mass loss rate (MLR) values after 180 s.

Table 5. Comparison of the Values Obtained as a Result of the Combustion Analysis of Composite Materials

Code	Time to Ignition (s)	Percentage Mass Loss (%)	Average Heat Release Rate 180 s (kW/m^2)	Average Effective Heat of Combustion 180 s (MJ/kg)	Mass Loss Rate 180 s (g/s)
UC	**23 (6.24)^b**	**78.4 (0.10)^a**	99.66 (6.15)^c	7.97 (0.28)^{bcd}	0.106 (0.01)^{bc}
U1	37 (6.02)^a	61 (0.41)^c	105 (7.08)^c	7.73 (0.27)^{bcd}	0.113 (0.01)^b
U2	25 (7.02)^b	53.8 (0.91)^d	87.47 2.62)^d	7.74 (0.30)^{bcd}	0.093 (0.01)^d
U3	26 (9.45)^b	46.7 (0.80)^e	74.40 (2.00)^e	7.27 (0.17)^{de}	0.087 (0.01)^{de}
U4	25 (1.52)^b	**16.1 (3.60)^h**	**64.01 (9.03)^f**	7.59 (0.79)^{cde}	**0.070 (0.1)^f**
FC	**37 (4.16)^a**	74.8 (0.10)^b	**153.4 (9.54)^a**	8.42 (0.40)^{ab}	**0.156 (0.01)^a**
F1	25 (1.52)^b	58.7 (0.26)^c	117.3 (0.48)^b	8.79 (0.06)^a	0.110 (0)^b
F2	31 (5.50)^{ab}	51.6 (0.15)^d	120.1 (3.11)^b	**8.94 (0.42)^a**	0.113 (0.01)^b
F3	28 (1)^{ab}	44.2 (0.75)^f	89.29 (0.82)^d	8.11 (0.39)^{bc}	0.095 (0.01)^{cd}
F4	27 (2)^b	36 (0.94)^g	65.30 (1.16)^f	**7.01 (0.21)^e**	0.080 m(0)^{ef}

Values in parentheses are the standard deviations; different letters in the TTI, PML A-HRR, A-EHC, and MLR columns indicate statistical differences at the 95% confidence level

Whereas the highest TTI (37 s) was obtained in the FC (100% wood fiber) composite boards produced using phenol formaldehyde resin, the lowest (23 s) was detected in the UC (100% wood fiber) composite board group using urea formaldehyde resin. No statistical difference was found between the UC (23 s), U2 (25 s), U3 (26 s), U4 (25 s), F1 (25 s), F4 (27 s) board groups and the F3 (28 s) and F2 (31 s) board groups. The lowest and highest TTI values occurred in board groups without stone wool added, which was attributed to the place where the ignition rod was positioned. Because the stone wool fibers do not show a homogeneous distribution in the composite boards produced at the laboratory scale and the ignition rod generates sparks at a small point, this was believed to have affected the results. Whereas the average TTI for all board groups produced with phenol formaldehyde resin was 29.6 s, the average of all board groups produced with urea formaldehyde resin was 27.2 s. According to these results, the resins used may also have been effective in the different ignition times. In the literature, it has been stated that many factors, such as ignition time, production conditions, type of resin used, and presence or absence of coating, are effective in MDF board performance. Ayrilmis (2006) reported that the ignition time in wood-based boards was related to the wood type, density, moisture content, material thickness and surface area, surface absorption, pyrolysis (irreversible deterioration of the chemical structure of wood due to high temperature) characteristics, thermal conductivity, specific heat, and amount of extractive substance. As the result of a combustion analysis performed on wood-based composite boards (PB, MDF, HDF, plywood, and laminate flooring) using a cone calorimeter, Lee *et al.* (2011) found the lowest TTI value (approximately 20 s) in the MDF boards. In their study, Tsantaridis and Östman (1998) determined that the TTI of 768 kg/m^3 density MDF board coated with melamine resin-impregnated paper was 45 s, and the TTI of uncoated 846 kg/m^3 density MDF board was 39 s. Akkus *et al.* (2021) obtained values varying between 71 and 44 s in the MDF boards on which electrostatic powder paint and water-based paint had been applied. Esmailpour *et al.* (2021) determined TTI values of between 18 and 26.5 s in wood fiber/camel thorn MDF boards produced using urea formaldehyde resin as a binder with different rates of added nano-wollastonite to improve combustion properties. Ma *et al.* (2013) reported that the TTI increased from 32 s to 190.5 s for MDF boards produced by adding ammonium phosphate at different levels to urea formaldehyde resin modified with melamine resin. Park and Lee (2008) found that chemical fire retardants applied to MDF material surfaces increased the TTI from 50 s to 75 s and stated that the TTI lengthened as the density of the material increased.

Combustion analysis results showed that the highest MLR (78.4%) was in the UC (100% wood fiber) board group, whereas the lowest value (16.1%) was obtained in the U4 hybrid (50% stone wool fiber + 50% wood fiber) board group. No statistical difference was found between the U1 (61%) and the F1 (58.7%) hybrid board groups or between the U2 (53.8%) and the F2 (51.6%) groups. It was determined that the increase in stone wool fiber led to a decrease in the MLR resulting from combustion. Figure 7 shows that the boards having high stone wool fiber ratios exhibited no fragmentation as a result of combustion, and that the increasing amounts of fragmentation and mass loss were clearly related to the increase in wood fiber content. According to the TS EN 13501 (2019) standard, bulk stone wool is in the “A1” (non-combustible) class, whereas medium-hardness wood-based fiberboards are classified as “D” (normal flammable). In MDF boards, minor mass losses occur at temperatures of about 40 to 100 °C. Rapid mass loss and the release of volatile organic gases, such as CO, CO_2, CH_4, and CH_3OH, occur with the decomposition of hemicellulose and cellulose at temperatures of 200 to 340 °C (Sun *et al.* 2012). Materials found in high amounts in stone wool, such as silicon dioxide (SiO_2), calcium oxide (CaO), and aluminum oxide (Al_2O_3), render the material resistant to fire (Yap *et al.* 2021). Stone wool fibers used in wood-based fiberboard prevent rapid mass loss during combustion.

The heat release rate (HRR) is a parameter that indicates the degree of capability of a material to dispel heat and its fire hazard potential. It is a critical factor in the spread of flame and fire growth in a room. When this value is low in a material, the degree of flammability in the environment is reduced. The highest HRR for 180 s (153.4 kW/m^2) was determined in the FC (100% wood fiber) composite board group, whereas the lowest (64 kW/m^2) was in the U4 hybrid-based composite board (50% wood fiber + 50% wool stone fiber).

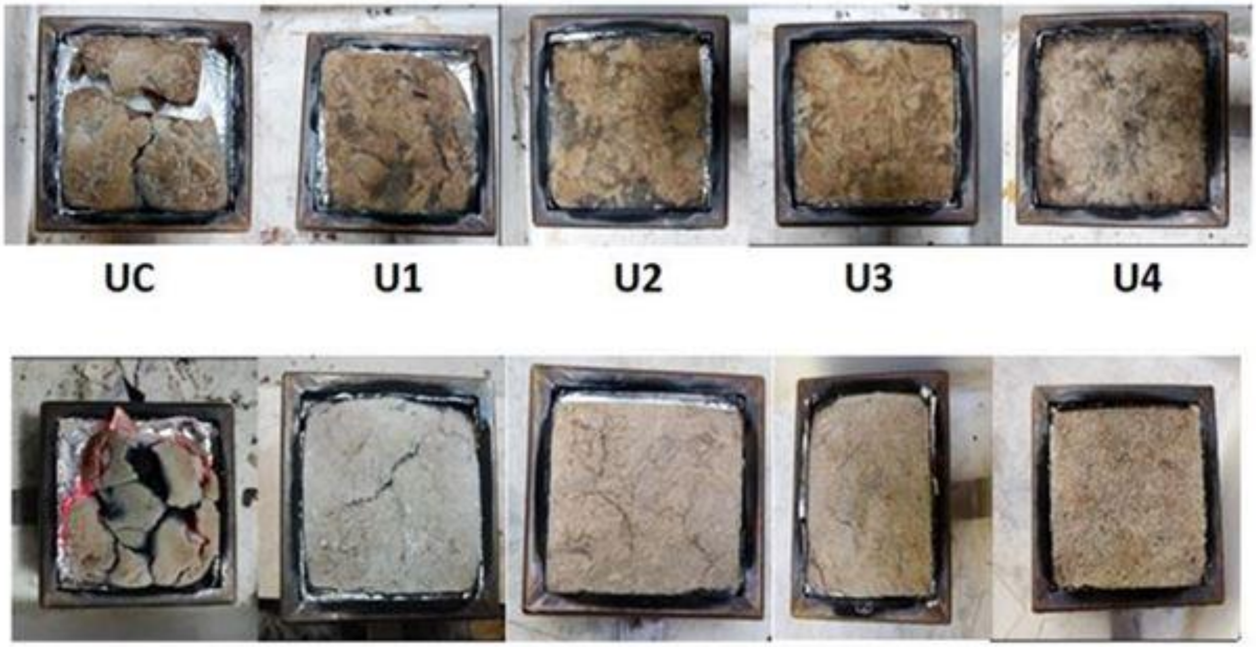

Fig. 7. Test samples after combustion

No statistical difference was found between the U4 (64.01 kW/m^2) and F4 (65.30 kW/m^2), between the UC (99.66 kW/m^2) and U1 (105 kW/m^2), between the F1 (117.3 kW/m^2) and F2 (120.1 kW/m^2), or between the U2 (87.47 kW/m^2) and F3 (89.29 kW/m^2) board groups. Depending on the increase in wood fiber content, the HRR of the hybrid-based composite boards also increased. White and Sumathipala (2013) investigated the combustion properties of MDF samples untreated and treated with various fire retardants using a cone calorimeter at a heat flow level of 50 kW/m^2. The results determined that the A-HRR of the untreated MDF samples was 160 to 168 kW/m^2 after 180 s, whereas this value was 84 to 109 kW/m^2 in the MDF samples treated with fire retardants. The surfaces of MDF boards were coated with graphite-based materials to improve their flame retardant properties, and examination of the combustion properties showed that the peak-HRR had been reduced from 213 kW/m^2 to 77.95 kW/m^2 (Seo *et al.* 2016). The HRR decreased significantly because of the increase in the stone wool fiber ratio in the boards.

After 180 s, the average effective heat of combustion (A-EHC) was the highest (8.94 MJ/kg) in the F2 board group, and the lowest (7.01 MJ/kg) in the F4 board group samples. No statistically significant difference was found between the F1 (8.79 MJ/kg) and F2 (8.94 MJ/kg) groups or between the UC (7.97 MJ/kg), U1 (7.73 MJ/kg), and U2 (7.74 MJ/kg) groups. Examination of the A-HRR values between the FC and F4 board groups and the UC and U4 groups revealed that the stone wool fiber reduced the A-HRR value. The A-EHC values in the produced board groups were similar to each other. Whereas the average A-EHC value of all board groups produced with urea formaldehyde resin was 7.66 MJ/kg, this value was 8.25 MJ/kg for all board groups produced with phenol formaldehyde resin. Except for the F4 group, the A-EHC values of the board groups produced with phenol formaldehyde resin were higher than in the boards produced with urea formaldehyde resin. After 180 s, A-EHC values of 8.89 to 9.18 MJ/kg were measured in electrostatic powder-coated MDF samples (Akkuş *et al.* 2021). In their research, Tsantaridis and Östman (1998) determined that the A-EHC of MDF board covered with melamine resin-impregnated paper was 13.3 MJ/kg, and that of uncoated MDF was 12.7 MJ/kg. In the same study, it was reported that the TTI, HRR, and A-EHC values of stone wool (because it does not burn) could not be determined at 50 kW/m^2 heat flux level in the cone calorimeter. White and Sumathipala (2013) found A-EHC values of 5.30 to 10.01 MJ/kg in MDF samples treated with fire-retardant chemicals, and 11.75 to 12.09 MJ/kg in the control (un-treated) MDF samples. Chen *et al*. (2012) determined A-EHC values of 12.1, 8.2, 4.8, and 2.8 MJ/kg, respectively, after the combustion analysis they performed on un-treated and 10, 20, and 30% ammonium polyphosphate-treated MDF samples.

The average MLR at the end of 180 s was highest (0.15 g/s) in the FC (100% wood fiber) board group, and the lowest (0.07 g/s) in the U4 hybrid (50% wood fiber + 50% wool stone fiber) board group. No statistical difference was found between the U1 (0.11 g/s), F1 (0.11 g/s), and F2 (0.11 g/s) board groups. The MLR decreased with the increase in the stone wool fiber ratio in the hybrid board. After the combustion analysis of uncoated MDF samples and those treated with coating paper, low pressure laminate, and direct coating, it was reported that the MLR rate was high (approximately 0.22 g/s) in the first 250 s, and then decreased in the following seconds (Park *et al.* 2013).

CONCLUSIONS

The study aimed to obtain a new hybrid board using stone wool fibers in the production of wood-based fiberboard. For this purpose, the hybrid fiberboards were subjected to bending, elasticity in bending, bond strength, water absorption, and thickness swelling tests, and combustion analyses. The results were as follows:

1. With the increase in stone wool fiber in the hybrid fiberboards, the densities, bending strength, modulus of elasticity, and bond strength were reduced in the samples produced with both urea formaldehyde resin and phenol formaldehyde resin. The lowest water absorption was in the U2 (70% wood fiber + 30% stone wool fiber) boards in the urea formaldehyde resin group, and the lowest water absorption was obtained in the FC (100% wood fiber) boards in the phenol formaldehyde resin group. For the boards produced with urea formaldehyde resin and soaked in water for 24 h, the lowest thickness swelling was obtained in the U4 (50% wood fiber + 50% stone wool fiber) boards, whereas for the boards produced with phenol formaldehyde resin, the lowest value was detected in the F3 (60% wood fiber + 40% stone wool fiber) boards. The stone wool fibers used in the hybrid boards inhibited water absorption and thickness swelling in these boards.
2. After the combustion analysis of hybrid-based boards using a cone calorimeter, the best TTI value in boards produced with urea formaldehyde resin was found in the U4 (50% wood fiber + 50% stone wool fiber) and U2 (70% wood fiber + 30% stone wool fiber) samples. For boards produced with phenol formaldehyde resin, the best value was obtained in the FC (100% wood fiber) samples. The lowest MLR from combustion was in the U4 (50% wood fiber + 50% stone wool fiber) boards in the urea formaldehyde group and in the F4 (50% wood fiber + 50% stone wool fiber) boards in the phenol formaldehyde group. The lowest values of A-HRR, A-EHC, and MLR after 180 s were obtained in the U4 and F4 board groups. The percent mass loss rates and the A-HRR, A-EHC, and MLR values of the boards after combustion decreased depending on the increase in the stone wool ratio.

3. The mechanical and physical properties of the material could be improved by including various additives in the wood fiber and stone wool fiber production process and by the binder resin to be used. Applying different modification processes to stone wool fibers could result in more durable boards. In addition, waste stone wool from construction debris could be used in hybrid fiberboard production. Using mineral fibers, such as stone wool, as a fire retardant in wood-based composite boards could be expected to reduce the use of chemical fire retardant compounds and thus, to make significant contributions to the protection of human health and the environment.

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