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Influence of vermiculite addition on particleboard properties with varied urea formaldehyde adhesive ratios

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Abstract:
Wood and wood-based panels are widely used in the construction and furniture industries; however, their inherently low fire resistance remains a major limitation. Vermiculite, a mineral that expands significantly at high temperatures, offers a promising solution to improve the fire resistance of such materials. This study aims to determine how varying vermiculite contents (0 %, 15 %, 20 %, 25 %) and urea–formaldehyde (UF) adhesive levels (12 %, 14 %, 16 %) jointly influence the physical, mechanical, and thermal performance of particleboards. Single-layer panels were manufactured under controlled pressing conditions, and their dimensional stability, strength properties, and thermal behavior were evaluated. Increasing vermiculite content led to higher thickness swelling and water absorption; for instance, at 25 % vermiculite, 2 h TS rose to 45.7 % in the 12 % UF group, while increasing UF to 16 % reduced this value to 31.4 %. Mechanical performance decreased with vermiculite addition: MOR declined from 15.77 MPa (control) to values below P1 requirements at higher vermiculite ratios, although increased UF partially mitigated this loss. In contrast, thermal properties improved markedly; mass loss during TGA decreased from 91.34 % (control) to 72.55 % at 25 % vermiculite with 16 % UF, indicating enhanced resistance to thermal degradation. These findings demonstrate that vermiculite substantially enhances thermal stability but compromises mechanical integrity, underscoring the need for careful balance between mineral content and adhesive level. Optimized vermiculite–UF combinations can support the development of particleboards for fire-resistant interior applications, offering valuable guidance for future material design and industrial implementation.

Keywords: Mechanical properties, particleboard, physical properties, thermal properties, vermiculite, urea-formaldehyde resins.

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Introduction

Various flame-retardant additives, particularly when used at higher loadings, are known to cause reductions in the physical and mechanical properties of wood-based panels. To compensate for these deteriorations, either higher amounts of adhesive or adhesives with stronger bonding capability are typically required. Therefore, an optimal selection of the UF resin ratio in relation to the amount of vermiculite is critical for achieving the desired balance between material performance and production cost.

This trade-off highlights the importance of determining the most appropriate adhesive content when incorporating vermiculite as a flame-retardant additive.

The usage and production of wood-based composites using wood and other ligocellulosic materials have been steadily increasing (Procházka *et al.* 2021). Wood-based products offer several advantages in their applications. They are easier to process than alternative materials, available in various colors and patterns, require minimal maintenance, and satisfy a wide range of consumer demands (Özlüsoylu and İstek 2015). Currently, wood and wood-based panels are widely used for structural, decorative, and functional purposes in interior and exterior architecture, construction, and furniture manufacturing. Moreover, wood is a renewable and sustainable material, which increases its importance and preference over non-renewable alternatives (Seo *et al.* 2016).

In particleboard production, wood particles are dried to the desired size, the adhesive is applied, and after forming the mat, the panels are manufactured by hot pressing.

During production, several factors such as the type of wood raw material, particle geometry, additional additives, adhesive type and amount, and pressing parameters have a direct influence on the final product quality (Ozkaya *et al.* 2007, İstek *et al.* 2023, Kurt 2022).

Depending on their application areas, particleboards are exposed to various biotic and abiotic factors that cause deformation, discoloration, decay, and loss of strength.

One of the primary objectives in particleboard production is to develop cost-effective, aesthetically appealing, and durable materials with sufficient resistance to these damaging factors (Dix and Roffael 1997). However, a major disadvantage of particleboards is their low resistance to combustion, which is particularly critical for indoor applications. In general, wood materials exhibit lower thermal stability compared to other construction materials (Jiang *et al.* 2010). Various methods and chemical additives have been developed to improve the fire resistance of wood products. Among them, phosphorus-based compounds such as monoammonium phosphate, diammonium phosphate, phosphoric acid, ammonium sulfate, boric acid, borax, ammonium chloride, and dicyandiamide, along with other flame retardants, are commonly used as preservative agents (Çavdar 2020).

Vermiculite is a magnesium-aluminosilicate clay mineral derived from volcanic lava rocks. When exposed to high temperatures, it expands significantly, resulting in increased volume and porosity. Vermiculite is naturally formed through the weathering and alteration of mica minerals, during which its bulk density decreases and it acquires a light, layered structure (Rashad 2016). It can adhere to various surfaces and exhibits excellent sound and thermal insulation properties. Moreover, when used as a flame retardant, vermiculite releases non-toxic smoke and gases, making it safe for both human health and the surrounding environment (Braganza *et al.* 1990, Wang *et al.* 2016a, Suvorov and Skurikhin, 2003, Nguyen *et al.* 2013).

In different studies, vermiculite was utilized to increase the combustion resistance of cellulosic-based composites. For instance, insulation materials were produced from waste newsprint, and additives such as vermiculite, perlite, zinc borate, and gypsum were incorporated either individually or in combination. The results indicated that vermiculite improved the thermal conductivity and combustion resistance of the materials, with the highest fire resistance observed in samples containing vermiculite. (Binici *et al.* 2016). In a similar study, the resistance to combustion of composites produced from waste cardboard, gypsum, pumice, perlite, vermiculite, and zeolite was investigated, and it was observed that vermiculite provided resistance to combustion when used alone and in mixture with other minerals (Binici 2016, Aksogan *et al.* 2018).

In another study, the thermal degradation and combustion performance of plywood produced with urea formaldehyde adhesive with added vermiculite increased the limit oxygen index (LOI) value with the use of vermiculite. As a result, combustion performance improved. In addition, vermiculite was reported to be a thermal insulator that slows pyrolysis and increases charring (Wang *et al.* 2016b).

Using flame-retardant additives can effectively slow down the burning rate of materials (Ergun 2023). To minimize harm to humans and the environment during fires, flame retardants that inhibit combustion and reduce smoke formation are essential, as they prevent the spread of flames across material surfaces (Aydın *et al.* 2016). Similarly, the incorporation of various flame retardants to reduce the flammability of wood materials is considered necessary, depending on their intended applications (Mensah *et al.* 2023). Flame retardants should possess a low ignition rate, diminish combustion intensity, produce minimal and slow smoke, and be non-toxic, while enhancing fire performance without impairing the material's properties. Additionally, they should be cost-effective and compatible with the functional requirements of their intended use (He *et al.* 2014).

In this context, the present study investigates the physical, morphological, mechanical, and thermal properties of particleboards manufactured using three different UF adhesive contents (12 %, 14 %, and 16 %) and four vermiculite levels (0 %, 15 %, 20 %, and 25 %).

Materials and methods

The density of expanded vermiculite ranges from 80 kg/m^3 to 120 kg/m^3, while its high melting point is between 1240 °C and 1430 °C. Its thermal conduction coefficient is between 0,04 W/mK and 0,12 W/mK. In addition, vermiculite is chemically inert, environmentally safe, and thermally stable. Expanded vermiculite was obtained from Agrikal (Antalya/Turkiye). Vermiculite was ground in a Wiley mill and then sieved through 0,25 mm diameter sieves before being used in particleboard production. The wood chips and urea-formaldehyde (UF) adhesive were supplied by a commercial particleboard factory. The chips have dimensions of 10,5 mm x 10,5 mm. Black pine (*Pinus nigra* J.F.Arnold) made up 50 % of the chip combination, followed by hornbeam (*Carpinus betulus* L.) (20 %), oriental beech (*Fagus orientalis* Lipsky.) (20 %), and black poplar (*Populus nigra* L.) (10 %). At 22 °C, the UF adhesive exhibited a viscosity of 220 mPa·s, a density between 1260 and 1280 kg/m^3, and a solid content of approximately 55 %.

Production of particleboard

Single-layer particleboards were made using the chips acquired from the particleboard facility. The chips were bagged to prevent air exposure and dried to a 1 % to 3 % moisture content before adhesive was applied. The gluing process was carried out in a mechanical rotary drum gluing machine (ECOMIX, 42750 Saint-Denis de Cabanne). The required amount of chips was placed into the drum and mixed with vermiculite at the designated ratios. Vermiculite was used in ratios of 15 %, 20 %, and 25 % of the dry chip weight. Then, the gluing process was carried out by mixing with UF adhesive. UF adhesive was also used in proportions of 12 %, 14 %, and 16 % by weight of whole dry chips. Vermiculite was added prior to adhesive application to ensure that the particles were fully coated with the UF resin. Table 1 shows the board groups and the number of boards produced.

Table 1: Compositions and number of particleboards produced.

Groups	Vermiculite rate (%)	UF rate (%)	Number of particleboards
1	0	12	3
		14	3
		16	3
2	15	12	3
		14	3
		16	3
3	20	12	3
		14	3
		16	3
4	25	12	3
		14	3
		16	3
Total			36

Following the assembly of the board, it was inserted into a hot press with measurements of 400 mm x 400 mm x 12 mm. Each group produced three particleboards. After completion, the boards were allowed to cool before being conditioned at a relative humidity of 65 % ± 5 % and a temperature of 20 °C ± 2 °C to reach equilibrium moisture content. Samples were collected to evaluate the qualities of the board.

The parameters used to manufacture the particleboard are shown in Table 2.

Table 2: Single layer particleboard production parameters.

Particleboard Production Parameters	Values
Press pressure (MPa)	6
Press temperature (°C)	180
Press time (s)	180
Target board density (kg/m^3)	650
Thickness (mm)	12

Characterization

The test panels were allowed to stabilize at ambient conditions for one week. The test specimens were prepared according to TS EN 326-1 (1999). The samples were then conditioned for one week in a controlled environment room at 20 °C ± 2 °C and 65 % ± 5 % relative humidity, as recommended by TS 642 ISO 554 (1997). The moisture content (MC) of the test panels was evaluated using TS EN 322 (1999), and their densities were assessed using TS EN 323 (1999). Thickness swelling (TS) was measured in accordance with TS EN 317 (1999). ASTM D1037-12 (2020) was used to test water absorption (WA).

According to TS EN 319 (1999) and TS EN 310 (1999), internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE), respectively, values were obtained. A scanning electron microscope (SEM) (Tescan Maia3 Xmu model) was used to analyze the particleboard morphologies. A thin layer of gold 5 nm thick was put into the samples to improve the conductivity of the particleboards. The SEM microscope was used to analyze microstructure images at a voltage of 20,0 kV. The ASTM C518-21 (2021) standard was adhered to while measuring the thermal conduction coefficients of the particleboards at 24 °C using a heat flux instrument (KEM QTM 500, Kyoto Electronics, Kyoto, Japan).

The materials were heated from room temperature to 800 °C for thermogravimetric (TG) and derivative thermogravimetric (DTG) analysis (Hitachi-STA 7300). With a gas flow rate of 50 mL per minute and a nitrogen environment, a heating rate of 10 ºC per minute was conducted. Each group underwent six repetitions of every test except TGA, thermal conduction coefficients, and SEM analyses. Using an ANOVA with the SPSS 16 software, the effects of different vermiculate concentrations on the mechanical and physical characteristics of the chipboard were evaluated at a 95 % confidence level ($p < 0,05$). The Duncan homogeneity test was used to identify statistically significant homogenous groupings.

Results and discussion

The homogeneity groups obtained from the one-way analysis of variance (ANOVA) for the moisture content and density values of the particleboards, depending on the vermiculite (V) ratio, are presented in Table 3. The same letters indicated in the column for the same UF ratio in the table represent the same homogeneity groups determined by the DUNCAN test.

Table 3: Moisture and density values of test samples.

Group No	V (%)	UF (%)	Moisture (%)	Density (kg/m^3)
1	0	12	6,30	697±38,46a
2	15	12	6,15	708±43,62a
3	20	12	6,42	714±44,32a
4	25	12	6,89	724±25,77a
5	0	14	7,30	703±37,44a
6	15	14	6,50	686±51,14a
7	20	14	6,17	697±29,38a
8	25	14	7,01	727±25,67b
9	0	16	7,52	669±52,23a
10	15	16	6,23	715±32,81b
11	20	16	6,48	714±40,21b
12	25	16	6,72	703±45,12b

±: standard deviation, there is no statistically significant difference between the same letters in the same column for the same adhesive ratio ($p<0,05$).

When Table 3 was examined, it was observed that the density of the panels increased linearly with the increasing vermiculite content in the 12 % UF group, while no linear trend was found for the 14 % and 16 % UF groups. The moisture values of the panel groups were within the limit values (5 % -13 %) specified in the TS EN 312 (2012) standard. When the target density value (650 kg/m^3) was considered in the study, the density values were within the 10 % tolerance limit specified in the TS EN 312 (2012) except for groups 4 and 8. In addition, there was no statistically significant difference between the density values of the experimental panels in the group where 12 % UF was used. İstek and Sıradağ (2013) stated that density changes up to 10 % in particleboards had no significant effect on board properties. In addition, many factors related to raw materials and production conditions can affect the board density.

The homogeneity groups of the average WA and TS values and standard deviation values of the experimental panels for 2 h, 24 h, and 72 h, obtained by the DUNCAN test, depending on the fixed UF usage, are given in Table 4.

Table 4: Average water absorption and thickness swelling values of test samples.

Codes	V (%)	UF (%)	2h-TS (%)	24h-TS (%)	72h-TS (%)	2h-WA (%)	24h-WA (%)	72h-WA (%)
1	0	12	35,77±3,62a	42,18±3,88a	45,50±4,95a	66,65±3,25a	78,04±3,45a	93,35±4,00a
2	15	12	54,42±7,20c	64,96±10,18c	71,06±11,96c	74,17±5,04b	88,38±4,76b	106,09±5,71b
3	20	12	38,04±2,95a	43,80±2,93a	47,14±3,50ab	67,77±5,31a	79,49±5,41a	95,02±8,24a
4	25	12	45,74±5,25b	51,79±4,65b	55,63±6,13b	70,67±5,18ab	85,90±6,46b	100,10±7,15ab
5	0	14	25,82±1,49a	31,45±2,75a	34,61±3,44a	55,26±7,75a	68,89±5,21a	82,38±6,48a
6	15	14	38,88±6,54c	45,29±7,08c	49,40±7,76b	72,16±6,64b	86,71±6,35b	103,16±7,35c
7	20	14	39,84±3,12c	45,80±3,55c	49,43±2,76b	69,02±4,73b	81,85±5,40b	96,23±6,19bc
8	25	14	33,30±4,64b	39,37±4,93b	42,78±6,12b	64,88±6,47b	78,90±7,47b	93,15±10,17b
9	0	16	23,31±4,43a	30,15±5,11a	32,45±6,14a	53,26±4,87a	67,10±2,86a	82,57±4,26a
10	15	16	31,17±3,57b	37,70±4,30bc	39,92±4,56ab	58,36±7,89ab	72,75±4,36ab	87,11±5,56a
11	20	16	36,19±4,62b	42,57±5,12c	44,09±6,03b	64,48±6,79b	78,38±7,46b	93,40±8,67a
12	25	16	31,38±5,27b	35,19±4,40ab	39,79±9,73ab	61,06±7,63b	75,10±8,94ab	90,14±13,64a

"±: standard deviation, there is no statistically significant difference between the same letters in the same column for the same adhesive ratio (p<0,05).

When Table 4 is examined, the lowest thickness swelling (TS) values after 2 h, 24 h, and 72 h were 23,31 %; 30,15 % and 32,45 %, respectively, for the 16 % UF group. These results indicate that dimensional stability improves with an increase in adhesive content. The highest TS and water absorption (WA) values were generally observed in panels with lower adhesive content and higher vermiculite ratios. Overall, as the vermiculite content increased, both TS and WA values at 2 h, 24 h, and 72 h increased compared to the control group (0 % V) for all adhesive levels. However, these increases became less pronounced as the UF adhesive content rose, suggesting that higher adhesive ratios mitigate the negative effects of vermiculite on dimensional stability. For 25 % vermiculite usage, the 2 h TS value, which is 45,74 % on average in the experimental group produced with 12 % UF, is 33,30 % and 31,38 % for 14 % UF and 16 % UF, respectively. Under the same conditions, the 2 h WA value, which is 70,67 % for (25 % V-12 % UF), is 64,88 % and 61,06 % for 14 % UF and 16 % UF, respectively. As a result, it was determined that there is a 32 % improvement in TS value and a 14 % improvement in WA value with an increase in adhesive amount from 12 % to 16 % in 25 %V usage. Statistically, there is no significant difference between the control groups (0 % V) and the experimental group using 20 % vermiculite for 2 h TS with 12

% UF usage. However, it was found that the experimental groups containing 15 % and 20 % vermiculite showed statistically significant differences compared to the control group. In the 14 % and 16 % UF adhesive groups, the differences between the control and all vermiculite-containing panels were also significant, indicating that vermiculite addition notably affected panel performance at these adhesive levels. The increase in both the TS and WA values did not show a linear trend with an increase in the amount of vermiculite for any of the panel groups. Many factors related to raw materials and production conditions can affect the dimensional properties of the panels (Li *et al.* 2017). This tendency held for vermiculate particles as the filler loading in the particleboards increased, and the water absorption rose dramatically. This may be attributed to the presence of additional voids in the interfacial region and a higher concentration of hydrophilic functional groups, such as hydroxyls, which can readily form hydrogen bonds with water molecules. These factors contribute to weaker interfacial adhesion between the matrix and the lignocellulosic components (Ghofrani *et al.* 2017). As mentioned earlier, this finding has been confirmed by several previous studies (Li *et al.* 2013, Ashori 2010). Although the 24 h thickness swelling (TS) values obtained from the experimental panels are higher than the 17% limit specified in TS EN 312 (2012) for non-load-bearing particleboards (Type P3) used in humid conditions, the panels can still be considered suitable for general-purpose applications. The homogeneity groups obtained by the DUNCAN test of the average modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) values measured according to the vermiculite ratios of the experimental panels under fixed UF usage and the standard deviation values are given in Table 5.

Table 5: Values of mechanical properties of test samples.

Codes	V (%)	UF (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
1	0	12	15,58±087b	2095,30±105,49a	0,42±0,03b
2	15	12	11,08±3,22a	1824,90±458,41a	0,24±0,05a
3	20	12	9,83±0,49a	1606,47±429,79a	0,21±0,04a
4	25	12	9,80±0,45a	1601,41±308,98a	0,16±0,06a
5	0	14	15,77±0,99b	2168,83±101,93b	0,43±0,06b
6	15	14	11,38±3,03a	1879,54±19,08ab	0,24±0,07a
7	20	14	10,19±1,50a	1675,23±69,70a	0,21±0,04a
8	25	14	10,00±1,82a	1669,98±306,58a	0,18±0,02a
9	0	16	14,50±0,58b	1962,86±192,65a	0,44±0,05b
10	15	16	12,06±2,14ab	1805,43±330,83a	0,28±0,15a
11	20	16	10,65±0,25a	1601,15±214,24a	0,23±0,15a
12	25	16	10,05±2,80a	1529,06±457,21a	0,22±0,06a
TS EN 312		P1	10,5	*	0,28
		P2	11	1800	0,40
		P3	15	2050	0,45

±: standard deviation, there is no statistically significant difference between the same letters in the same column for the same adhesive ratio (p<0,05).*: P1: General-purpose panels used in dry conditions, P2: Panels used in interior fittings (including furniture) under dry conditions, P3: Load-bearing panels used in humid conditions.

When Table 5 is examined, it is observed that the highest MOR, MOE, and IB values were obtained in the control groups where no vermiculite was used. For MOR, the highest values were 15,77 MPa; 15,58 MPa and 14,50 MPa in the control groups containing 14 %, 12 %, and 16 % UF adhesive, respectively. The best MOE values were determined to be 2168,83 MPa; 2095,30 MPa, and 1962,86 MPa, respectively, for 14 %, 12 %, and 16 % UF usage. While the highest IB values were obtained in the control groups, a linear decrease in IB values with increasing vermiculite usage rate was observed for all groups, and a linear improvement was observed depending on the increasing UF usage rate. For MOR and MOE, it was observed that the increase in UF adhesive content in the control groups did not result in a linear improvement. However, the experimental panels containing different vermiculite ratios exhibited a linear increase in both MOR and MOE values as the UF content increased. Statistically, significant differences were observed between the control group and the groups containing vermiculite at 12 % and 14 % UF adhesive levels for MOR. At 16 % UF, significant differences were found only for the panels containing 20 % and 25

% vermiculite, compared to the control group. For MOE, no significant difference was found between the control and experimental groups using vermiculite for 12 % and 16 % UF usage, but a significant difference was found between the control group and all groups using vermiculite for 14 % UF. For IB, the difference between the control and vermiculite groups was significant for all adhesive usage rates, while the difference between the vermiculite groups was insignificant. According to the TS EN 312 (2012) standard, it was determined that the results obtained from the control and 15 % vermiculite, 12 % and 14 % adhesive usage, and all panel groups except for 25 % vermiculite in 16 % UF usage meet the requirements of P1 panel class for MOR. For MOE, it was determined that the value obtained from the control and experimental panels using 15 % vermiculite for all adhesive usage rates meets the requirement of the P2 panel class. For MOR, among all groups containing vermiculite, only the panel with 15 % vermiculite and 16% UF adhesive met the minimum requirement specified for the P1 panel class. The mechanical properties were found to decrease with increasing vermiculite addition and improve with increasing adhesive usage rate in production. In addition, IB values can meet the standards less than MOR and MOE. This situation can be predicted due to the importance of adhesive-chip bonding for IB resistance compared to MOR and MOE and the negative effect of vermiculite on internal bonding. However, numerous factors related to raw materials and production conditions can influence the mechanical properties of the panels. It has been reported that wood-based composites also exhibit a decrease in MOR and MOE values with increasing vermiculite content, consistent with the findings of this study (Ghofrani *et al.* 2017). Previous research has shown that chemical bonding between constituents can be challenging due to differences in their chemical nature, such as the polar structure of wood and the non-polar structure of polymers (Durmaz 2022, Ndiaye *et al*. 2011). This reduction in bonding efficiency may result from the fact that wood fibers and melamine-urea-formaldehyde (MUF) adhesives are organic, whereas vermiculite is inorganic in nature. In addition, it has been emphasized that the accumulation of vermiculite on fiber surfaces at higher ratios can weaken intermolecular forces and reduce sliding friction between MDF components, thereby lowering MOR and MOE values (Wang *et al.* 2016b, Hashim *et al.* 2009). The thermal conduction coefficients of the test samples measured according to the increasing amount of vermiculite in the use of fixed adhesives are given in Figure 1.

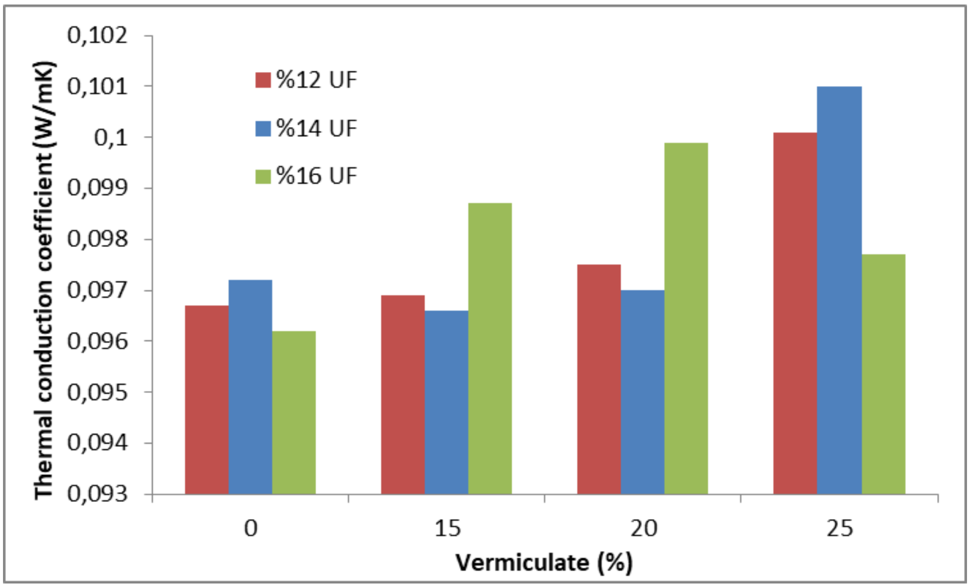

Figure 1: Thermal conduction coefficients of particleboards.

When Figure 1 is examined, it is observed that there are non-linear changes in thermal conduction coefficients with increasing vermiculite amount for all adhesive usage groups. It was calculated that the thermal conduction coefficients increased by 3,91 % in the experimental group using 14 % UF and 25 % vermiculite compared to the control sample. Generally, the panel groups using vermiculite compared to the control sample show an increase in density. This increase can be evaluated as the result of more compression of low specific gravity vermiculite in the panel as the amount of use increases. The density and thermal conduction coefficient of particleboard made from wood and polystyrene wastes increased as the polystyrene content increased (Akinyemi *et al.* 2019).

It was understood that the increase in the density of the panels causes high thermal conduction coefficients. Several studies have reported that increasing porosity in the material, resulting from higher vermiculite content, leads to a reduction in thermal conductivity and consequently improves insulation performance. (Sutcu 2015, Koksal *et al.* 2015, Binici 2016).

The thermal properties of the particleboards were analyzed to compare their behavior with and without vermiculite addition. The analysis was conducted under a nitrogen atmosphere using thermogravimetric (TG) and derivative thermogravimetric (DTG) methods. The results are summarized in Table 6. In this context, T_{10} % represents the temperature at which an initial 10 % mass loss occurred, while T_{50}% corresponds to the temperature at which 50 % mass loss was recorded.

Table 6: Summary results of TG and DTG curves of particleboards.

Codes	$T_{10\%}$ (°C)	$T_{50\%}$ (°C)	Mass loss (%)
1	259	344	91,34
2	259	351	82,12
3	259	351	81,20
4	260	352	78,38
5	258	353	83,26
6	259	352	81,08
7	261	353	80,47
8	268	354	77,97
9	254	348	81,22
10	261	355	79,16
11	267	355	77,23
12	268	359	72,55

$T_{10\%}$ was found between the temperatures of 254 °C and 268 °C, and $T_{50\%}$ was found between 344 °C and 359 °C. The particleboard without vermiculate had a maximum mass loss of 91,34 % at a thermal degradation temperature of 800 °C. On the other hand, the particleboard with a 25 % vermiculate and 16 % adhesive combination had the lowest mass loss of 72,55 %. The inclusion of vermiculate improved the thermal stability of the particleboard. Because of the vermiculate low permeability coefficient, it improves fire resistance and acts as an oxygen barrier (Wang *et al.* 2016b). As a result, the porous structure of vermiculate reduced heat conduction and oxygen circulation (Diler *et al.* 2024). The TG-DTG curves of experimental groups with varying vermiculite ratios produced with 12 % UF, 14 % UF, and 16 % UF are presented in Figure 2a, Figure 2b, and Figure 2c, respectively.

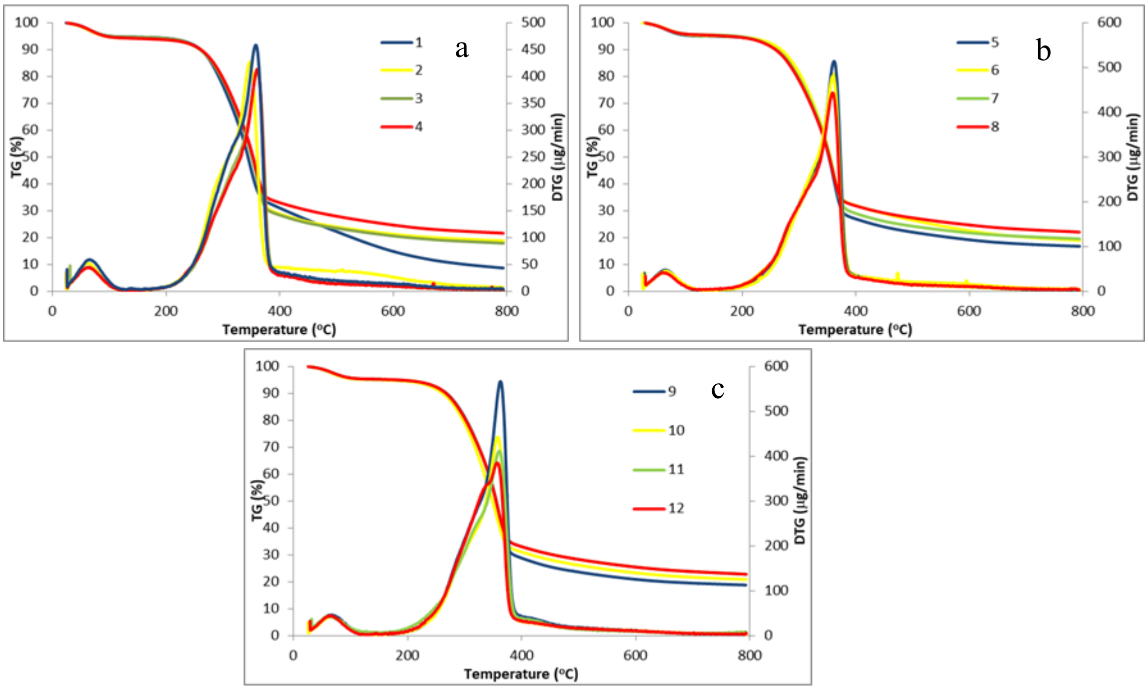

Figure 2: Thermal analysis of particleboards produced with (a): 12 % UF, (b): 14 % UF, (c): 16 % UF.

The compositional and thermal characteristics of various materials, including particleboards composed of wood particles bonded with adhesives, were analyzed using thermogravimetric (TGA) and derivative thermogravimetric (DTG) techniques.

The thermal degradation behavior of the particleboards varied depending on factors such as the type and amount of adhesive, particle distribution and size, pressing conditions, and the presence of fillers or additives (Islam *et al.* 2021). The heat disintegration of particleboards consisted of three major stages: moisture evaporation, hemicellulose and cellulose degradation, and lignin and adhesive degradation. According to the TG analysis, these stages took place at approximately below 100 °C, between 200 °C and 400 °C, and above 400 °C, respectively (Evangelopoulos *et al.* 2015, Altay *et al.* 2024).

As seen in Figure 2a, Figure 2b, and Figure 2c, the samples containing vermiculite exhibited lower mass loss compared to the control sample as the temperature increased. The extent of mass loss varied depending on the amount of adhesive used during production, and the difference between the vermiculite-containing and control samples decreased with higher adhesive content. In general, mass loss decreased with increasing vermiculite content, which can be attributed to the enhanced anti-oxidation behavior and improved thermal stability of the material. This effect is likely due to the presence of the silicate layer in vermiculite, which acts as a protective barrier against thermal degradation.

The DTG research showed that the material's burning rate decreased as the amount of vermiculate added to the particleboards increased. As the vermiculite content in particleboards increases, as evident from the results of the DTG analysis, a decrease in the mass loss rate is observed. As the vermiculite content increases in particleboards, they may have delayed ignition and exhibited increased fire resistance. It is stated that the thermal properties of inorganic fillers improve in wood-based boards (Ergun *et al.* 2023, Çavdar 2020).

SEM images of the test samples containing different amounts of vermiculite are presented in Figure 3. Distinct vermiculite flakes can be observed in the samples with 15 %, 20 %, and 25 % vermiculite, whereas they are absent in the control group. Notably, Figure 3b highlights the porous morphology of the vermiculite particles, as indicated by the red circles. This observation suggests that the porous structure and layered morphology of vermiculite may weaken the adhesive bonding between wood chips, potentially leading to a reduction in both physical and mechanical performance of the panels.

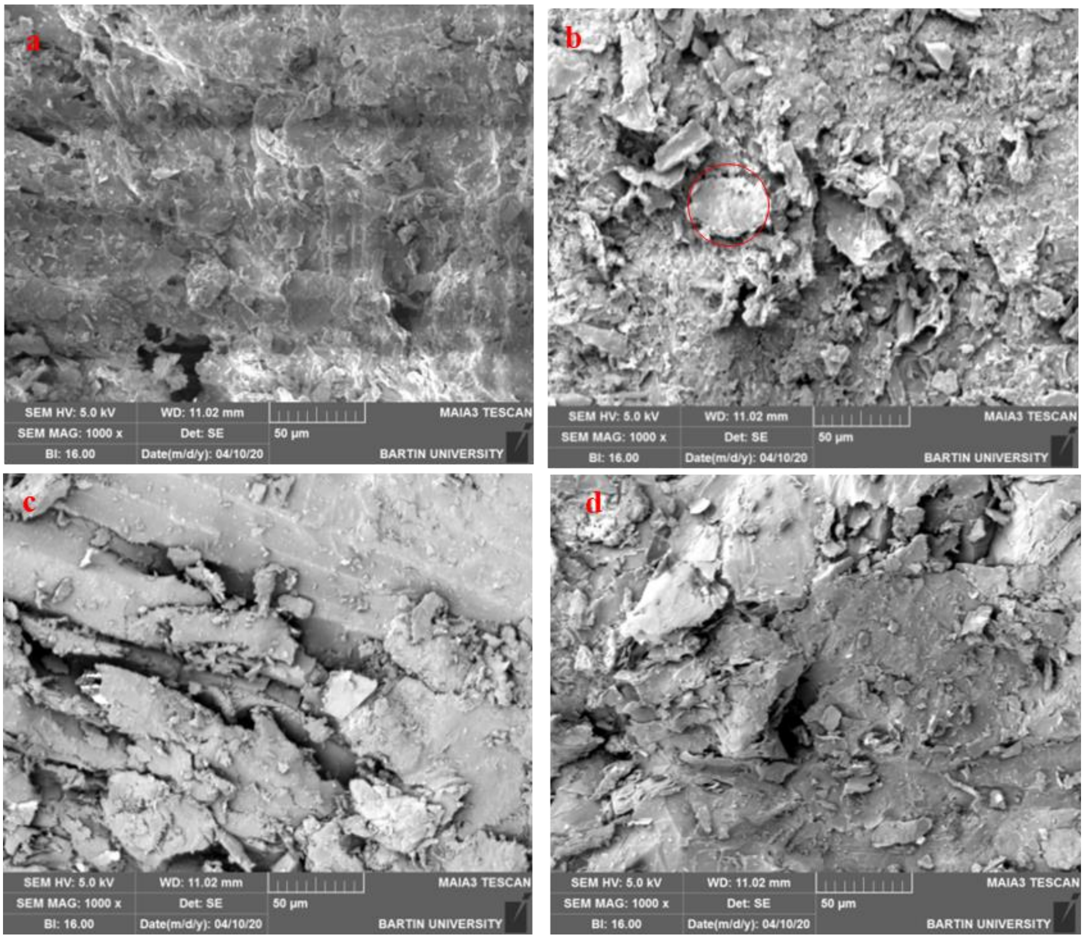

Figure 3: SEM images of test samples a: Control, b: 15 % Vermiculite, c: 20 % Vermiculite, d: 25 % Vermiculite.

A study indicates that vermiculite flakes create pores, increasing the porosity of the structure and decreasing the bulk density (Sutcu 2015). The results obtained from our study are consistent with the literature, revealing that the adverse effects on the physical properties of the panels, such as water absorption and thickness swelling rates, are associated with this condition. Consequently, these effects lead to a noticeable decline in the mechanical performance of the particleboards. In similar studies, aggregation formed from using different fillers was detected by SEM images, and this aggregation negatively affected the mechanical and physical properties of the produced materials (Ozyhar 2020).

Conclusions

This study demonstrates that both the vermiculite content and the UF adhesive ratio have a decisive influence on the physical, mechanical, and thermal performance of particleboards. The results indicate that increasing vermiculite levels results in non-linear changes in MOR, MOE, and IB values, depending on the adhesive content used. Higher vermiculite ratios increased water absorption and thickness swelling, while simultaneously enhancing thermal stability, as indicated by lower mass loss and higher degradation temperatures (T10% and T50%). SEM analysis revealed vermiculite flakes and a more porous structure, which help explain the reduction in bonding performance. The study clearly illustrates the inherent trade-off between improving thermal performance through vermiculite addition and maintaining mechanical integrity under lower UF adhesive levels. Therefore, determining the appropriate balance between vermiculite content and adhesive ratio is essential for producing particleboards with optimal performance characteristics. Future research may focus on optimizing resin formulations, deepening the understanding of mineral–adhesive compatibility, and developing performance-based standards for thermally enhanced wood-based composites. Additionally, this study provides a foundation for broader investigations into the integration of mineral fillers in wood composite materials, contributing to the advancement of composite design and material development.

Authorship contributions

A. İ.: Conceptualization, methodology, material testing, and original draft. I. Ö.: Methodology, material testing, formal and statistical analysis, and original draft. S. M. O.: Material preparation and testing, writing and editing of original draft. M. E. E.: Data curation, writing and editing of original draft.

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Declaration of interest

The authors declare no conflict of interest.

References:

Akinyemi, B.A.; Okonkwo, C.E.; Alhassan, E.A.; Ajiboye, M. 2019. Durability and strength properties of particle boards from polystyrene-wood wastes. *Journal of Materials Cycles and Waste Management* 21(6): 1541-1549. https://doi.org/10.1007/s10163-019-00905-6

Aksogan, O.; Resatoglu, R.; Binici, H. 2018. An environment friendly new insulation material involving waste newsprint papers reinforced by cane stalks. *Journal of Building Engineering* 15: 33-40. https://doi.org/10.1016/j.jobe.2017.10.011

Altay, Ç.; Özdemir, E.; Baysal, E.; Ergün, M.E.; Toker, H. 2024. Physical, mechanical, and thermal characteristics of alkaline copper quaternary impregnated Oriental beech wood. *Maderas. Ciencia y Tecnología* 26(3): 1-10. https://doi.org/10.22320/s0718221x/2024.03

Ashori, A. 2010. Hybrid composites from waste materials. *Journal of Polymers and the Environment* 18(1): 65-70. https://doi.org/10.1007/s10924-009-0155-6

American Society for Testing and Materials. 2020. Standard test methods for evaluating properties of wood-base fiber and particle panel materials. ASTM D1037-12. ASTM: West Conshohocken, PA, USA. www.astm.org/Standards/D1037.htm
American Society for Testing and Materials. 2021. Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. ASTM C518-21. ASTM: West Conshohocken, PA, USA. https://www.astm.org/c0518-21.html
Aydın, D.Y.; Gürü, M.; Ayar, B.; Çakanyıldırım, Ç. 2016. Bor bileşiklerinin alev geciktirici ve yüksek sıcaklığa dayanıklı pigment olarak uygulanabilirliği. *Journal of Boron* 1(1): 33-39. https://dergipark.org.tr/tr/download/article-file/173986
Binici, H. 2016. Atık mukavva, alçı, pomza, perlit, vermikülit ve zeolit ile yapılan kompozitlerin yangın direncinin araştırılması. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi* 31(1): 1-10. https://doi.org/10.21605/cukurovaummfd.317714
Binici, H.; Sevinç, A.H.; Eken, M.; Efe, V. 2016. Atık gazete kağıdından yalıtım malzemesi üretimi. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi* 30(2): 13-24. https://doi.org/10.21605/cukurovaummfd.242772
Braganza, L.F.; Crawford, R.J.; Smalley, M.V.; Thomas, R.K. 1990. Swelling of n-butylammonium vermiculite in water. *Clays and Clay Minerals* 38(1): 90-96. https://doi.org/10.1346/CCMN.1990.0380112
Çavdar, A.D. 2020. Effect of zeolite as filler in medium density fiberboards bonded with urea formaldehyde and melamine formaldehyde resins. *Journal of Building Engineering* 27. e101000. https://doi.org/10.1016/j.jobe.2019.101000
Diler, H.; Durmaz, S.; Acar, M.; Aras, U.; Erdil, Y.Z. 2024. The effect of vermiculite on flame retardancy, physical and mechanical properties of wood plastic composites. *BioResources* 19(1): 183-194. https://doi.org/10.15376/biores.19.1.183-194
Dix, B.; Roffael, E. 1997. Einfluß der verkernung und des baumalters auf die eigenschaften von spanplatten aus kiefernholz (*Pinus sylvestris*). *Holz Roh- Werkst* 55(2): 103-109. https://doi.org/10.1007/BF02990526
Durmaz, S. 2022. Effect of wood flour content on the properties of flat-pressed wood plastic composites. *Wood Research* 67(2): 302-310. https://doi.org/10.37763/wr.1336-4561/67.2.302310
Ergun, M.E. 2023. Activated carbon and cellulose-reinforced biodegradable chitosan foams. *BioResources* 18(1): 1215-1231. https://doi.org/10.15376/biores.18.1.1215-1231
Ergun, M.E.; Ozen, E.; Yildirim, N.; Dalkilic, B.; Baysal, E. 2023. Mechanical and thermal properties of polyvinyl acetate foams reinforced with biopolymers. *Cellulose Polymers* 42(3-4): 156-173. https://doi.org/10.1177/02624893231193501
Evangelopoulos, P.; Kantarelis, E.; Yang, W. 2015. Investigation of the thermal decomposition of printed circuit boards (PCBs) via thermogravimetric analysis (TGA) and analytical pyrolysis (Py-GC/MS). *Journal of Analytical and Applied Pyrolysis* 115: 337-343. https://doi.org/10.1016/j.jaap.2015.08.012
Ghofrani, M.; Ashori, A.; Mehrabi, R. 2017. Mechanical and acoustical properties of particleboards made with date palm branches and vermiculite. *Polymer Testing* 60: 153-159. https://doi.org/10.1016/j.polymertesting.2017.03.028
Hashim, R.; Sulaiman, O.; Kumar, R.N.; Tamyez, P.F.; Murphy, R.J.; Ali, Z. 2009. Physical and mechanical properties of flame retardant urea formaldehyde medium density fiberboard. *Journal of Materials Processing Technology* 209(2): 635-640. https://doi.org/10.1016/j.jmatprotec.2008.02.036
He, X.; Li, X.; Zhong, Z.; Yan, Y.; Mou, Q.; Yao, C.; Wang, C. 2014. The fabrication and properties characterization of wood-based flame retardant composites. *Journal of Nanomaterials* 2014. e878357. https://doi.org/10.1155/2014/878357

İstek, A.; Yiğittap, Ö.; Özlüsoylu, İ. 2023. Effect of chip temperature during bonding on particleboard properties. *Maderas. Ciencia y Tecnología* 25(17): 1-8. https://doi.org/10.4067/s0718-221x2023000100417
İstek, A.; Sıradag, H. 2013. The effect of density on particleboard properties. In: *Proceedings of the International Caucasian Forestry Symposium*, 23-26 October, Artvin, Turkey, pp. 932-938. https://www.semanticscholar.org/paper/THE-EFFECT-OF-DENSITY-ON-PARTICLEBOARD-PROPERTIES-Istek-Sirada%C4%9F/271d53a520ee7f5f39d33fe9bf78be1bfc884be7
Jiang, J.; Li, J.; Hu, J.; Fan, D. 2010. Effect of nitrogen phosphorus flame retardants on thermal degradation of wood. *Construction and Building Materials* 24(12): 2633-2637. https://doi.org/10.1016/j.conbuildmat.2010.04.064
Koksal, F.; Gencel, O.; Kaya, M. 2015. Combined effect of silica fume and expanded vermiculite on properties of lightweight mortars at ambient and elevated temperatures. *Construction and Building Materials* 88: 175-187. https://doi.org/10.1016/j.conbuildmat.2015.04.021
Kurt, R. 2022. Control of system parameters by estimating screw withdrawal strength values of particleboards using artificial neural network-based statistical control charts. *Journal of Wood Science* 68. e64. https://doi.org/10.1186/s10086-022-02065-y
Li, L.; Zhou, X.; Li, Y.; Gong, C.; Lu, L.; Fu, X.; Tao, W. 2017. Water absorption and water/fertilizer retention performance of vermiculite modified sulphoaluminate cementitious materials. *Construction and Building Materials* 137: 224-233. https://doi.org/10.1016/j.conbuildmat.2017.01.061
Li, X.; Lei, B.; Lin, Z.; Huang, L.; Tan, S.; Cai, X. 2013. The utilization of organic vermiculite to reinforce wood-plastic composites with higher flexural and tensile properties. *Industrial Crops and Products* 51: 310-316. https://doi.org/10.1016/j.indcrop.2013.09.019
Mensah, R.A.; Jiang, L.; Renner, J.S.; Xu, Q. 2023. Characterisation of the fire behaviour of wood: From pyrolysis to fire retardant mechanisms. *Journal of Thermal Analysis and Calorimetry* 148(4): 1407-1422. https://doi.org/10.1007/s10973-022-11442-0
Islam, M.N.; Adib, A.; Dana, N.H.; Das, A.K.; Faruk, M.O.; Siddique, M.R.H.; Agar, D.A.; Larsson, S.H.; Rudolfsson, M.; Ashaduzzaman, Md.; Iftekhar, M.S. 2021. Raw natural rubber latex-based bio-adhesive for the production of particleboard: formulation and optimization of process parameters. *RSC Advances* 11(46): 28542-28549. https://doi.org/10.1039/D1RA05307H
Ndiaye, D.; Matuana, L.M.; Morlat-Therias, S.; Vidal, L.; Tidjani, A.; Gardette, J.L. 2011. Thermal and mechanical properties of polypropylene/wood-flour composites. *Journal of Applied Polymer Science* 119(6): 3321-3328. https://doi.org/10.1002/app.32985
Nguyen, A.N.; Reinert, L.; Lévêque, J.M.; Beziat, A.; Dehaudt, P.; Juliaa, J.F.; Duclaux, L. 2013. Preparation and characterization of micron and submicron-sized vermiculite powders by ultrasonic irradiation. *Applied Clay Science* 72: 9-17. https://doi.org/10.1016/j.clay.2012.12.007
Ozkaya, K.; Cemil Ilce, A.; Burdurlu, E.; Aslan, S. 2007. The effect of potassium carbonate, borax and wolmanit on the burning characteristics of oriented strandboard (OSB). *Construction and Building Materials* 21(7): 1457-1462. https://doi.org/10.1016/j.conbuildmat.2006.07.001
Ozyhar, T. 2020. Application of mineral filler in surface layer of three-layer particle board and its effect on material properties as a function of filler content. *International Wood Products Journal* 11(3): 109-114. https://doi.org/10.1080/20426445.2020.1735753
Özlüsoylu, İ.; İstek, A. 2015. Mobilya üretiminde kullanılan panellerden salınan formaldehit emisyonu ve insan sağlığı üzerine etkileri. *Selcuk University Journal of Engineering Sciences* 14(2): 213-227. https://sujes.selcuk.edu.tr/sujes/article/view/228/178

Procházka, P.; Honig, V.; Bouček, J.; Hájková, K.; Trakal, L.; Soukupová, J.; Roubík, H. 2021. Availability and applicability of wood and crop residues for the production of wood composites. *Forests* 12(5). e641. https://doi.org/10.3390/f12050641
Rashad, A.M. 2016. Vermiculite as a construction material - A short guide for Civil Engineer. *Construction and Building Materials* 125: 53-62. https://doi.org/10.1016/j.conbuildmat.2016.08.019
Seo, H.J.; Kim, S.; Huh, W.; Park, K.W.; Lee, D.R.; Son, D.W.; Kim, Y.S. 2016. Enhancing the flame-retardant performance of wood-based materials using carbon-based materials. *Journal of Thermal Analysis and Calorimetry* 123(3): 1935-1942. https://doi.org/10.1007/s10973-015-4553-9
Sutcu, M. 2015. Influence of expanded vermiculite on physical properties and thermal conductivity of clay bricks. *Ceramics International* 41(2, Part B): 2819-2827. https://doi.org/10.1016/j.ceramint.2014.10.102
Suvorov, S.A.; Skurikhin, V.V. 2003. Vermiculite - a promising material for high-temperature heat insulators. *Refractories and Industrial Ceramics* 44(3): 186-193. https://doi.org/10.1023/A:1026312619843
Turkish Standards Institution. 1997. Standard atmospheres for conditioning and/or testing; Specifications. TS 642 ISO 554. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073088079089109078101067066109109072
Turkish Standards Institution. 1999. Wood-Based Panels-Determination of modulus of elasticity in bending and of bending strength. TS EN 310. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073081043116097068090054109087073106
Turkish Standards Institution. 2012. Particleboards - Specification. TS EN 312. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073086075116114114080065054097119079
Turkish Standards Institution. 1999. Particleboards and fibreboards- Determination of swelling in thickness after immersion in water. TS EN 317. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073085120113055076085053105079054080
Turkish Standards Institution. 1999. Particleboards and fibreboards- Determination of tensile strength perpendicular to the plane of the board. TS EN 319. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073102114047051073055104118100104110
Turkish Standards Institution. 1999. Wood-based panels- Determination of moisture content. TS EN 322. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073086053053069116117111080116115097
Turkish Standards Institution. 1999. Wood-Based panels- Determination of density. TS EN 323. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073087100068068087074054118116055115
Turkish Standards Institution. 1999. Wood-Based panels- Sampling, cutting and inspection- Part 1: Sampling test pieces and expression of test results. TS EN 326-1. TSE: Ankara, Turkey. https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073090076116057120114090121080106051

Wang, F.; Gao, Z.; Zheng, M.; Sun, J. 2016a. Thermal degradation and fire performance of plywood treated with expanded vermiculite. *Fire and Materials* 40(3): 427-433. https://doi.org/10.1002/fam.2297

Wang, J.; Wang, F.; Gao, Z.; Zheng, M.; Sun, J. 2016b. Flame retardant medium-density fiberboard with expanded vermiculite. *BioResources* 11(3): 6940-6947. https://doi.org/10.15376/biores.11.3.6940-6947