PRODUCTION OF COMPOSITE PARTICLEBOARD FROM WASTE PLUM PITS (*PRUNUS DOMESTICA*) AND IMPROVEMENT OF ITS CHARACTERISTICS

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This paper deals with investigating the feasibility of using waste plum pits in the production of composite particleboard materials and the improvement of their mechanical and physical properties. Biodegradability, flammability and water absorption are the primary disadvantages of wood-based composites, which reduce their service life. In this experimental study, waste colemanite was used to decrease the known flammability of wood composites. Phenol formaldehyde (PF) was used to increase the water resistance and prevent biodegradability of the prepared materials, and hemp fiber was added to increase their mechanical strength. Thus, the objective was to avoid the disadvantages of wood-based materials. Based on the results of the flexural strength test, the optimum polymer composite material production parameters were determined to be as follows: 0.50 filler/binder ratio, 56 kg/cm^2 moulding pressure and 0.75 hemp fiber ratio. According to the results of the experiments, the use of waste colemanite in the production of composite materials improves their non-flammability, while decreasing flexural and screw withdrawal strengths. It was determined that waste plum pits could be used to substitute for wood chips, as an alternative filler material in the production of composite materials. As a result, eco-friendly polymer composite materials were produced from waste plum pits, hemp fiber, and waste colemanite. The obtained composite materials are compliant with applicable standards and are suitable for application as building materials for use in both interior and exterior space.

Keywords: composite particleboard, plum pit, boron, hemp fiber, flame retardant, LOI, water resistance

INTRODUCTION

Wood composite materials are produced by combining wood fiber, flake, sawdust, veneer, or paper materials with different adhesives, resins, or water-repellent materials.[1] Examples of wood-based composite materials are plywood, oriented strand board (OSB), particleboard, medium-density fiberboard (MDF), wood plastic composite (WPC), parallel strand lumber (PSL), hard fiberboard (HB) and inorganic bonded board.[2] Polymer chemical binders, such as polyvinyl acetate (PVAc), phenol-formaldehyde (PF), urea-formaldehyde (UF), melamine urea formaldehyde (MUF), and emulsion polymer isocyanate (EPI), are generally used in the production of wood composite materials.[3] In addition, organic binder materials, such as starch, citric acid, tannin, blood, casein and sugar, are used in the production of these composite materials.[4] Moreover, PF resin is used to protect wood composite materials against termites or prevent their biological deterioration caused by fungi and mold, as well as to increase their moisture resistance.[5] On the other hand, experimental studies on formaldehyde reveal that this material is harmful to human health, being toxic and carcinogenic.[6-8]

There have been numerous studies in recent years aimed at reducing the use of formaldehyde-based binders in the production of wood composite materials. These studies include those in which organic materials, such as molasses, starch, sugar, protein and lignin, are substituted for formaldehyde.[8-10]

Construction, furniture, automotive, and packaging are the leading sectors where wood-based composite materials are used. Forest areas are rapidly decreasing all over the world, as the demand for wood-based products is increasing.[11] The increased demand for wood products, population growth, and the development of new applications lead to a decline in the forest cover. To prevent deforestation, it is crucial to use non-wood alternative raw materials to replace wood.[12] Waste materials, such as agricultural residues and wood processing wastes, including coarse and fine sawdust, branches and bark, come to the forefront as alternative raw material sources.[12,13]

During the processing of industrial and agricultural products, residues such as plant fibers and stems, leaves, roots, bark, pomace, pulp, bran and seeds, are generated.[14] In some studies conducted to produce composite materials, agricultural wastes, such as peanut shell,[15] mango seed shell,[16] cherry stone,[17] water melon peel,[18] orange peel,[19] kiwi stalk,[20] apple and cherry prunings,[21] tomato stalk,[22] grapevine prunings,[23] pineapple leaves,[24] palm leaves,[25] banana stem and coir fiber,[26] and papaya stem,[27] have been used as alternatives to wood.

In this study, plum pits, hemp fibers and molasses are considered in the development of composite particleboard. Plum is a stone fruit belonging to the genus Prunus cultivated all over the world. According to data of 2018, 3.9 million tons/year of plums were produced worldwide. According to data of 2019, the main plum-producing countries are China (~54%), Romania (~7%), Serbia (~3.4%), USA (~3.1%), Turkey (~2.6%), and India (~2.2%).[28] Plum fruit is used in the production of fruit juice, jam, jelly, alcohol, pharmaceuticals, and cosmetics.[29] Hemp (*Cannabis sativa L.*) is cultivated for its seeds and fiber. Hemp fibers are traditionally employed in the production of paper, textiles, building materials, and insulation.[30] According to data of 2019, the largest hemp-producing countries are China (200,000 ha), USA (32,000 ha) and France (14,500 ha).[31] Meanwhile, molasses are vegetable wastes produced during sugar production from beets or sugar cane in sugar refineries. This material contains high amounts of polymer sugars.[32] Molasses are obtained in amounts of approximately 4~7 kg from 100 kg of sugar beet and 35~40 kg from 1 ton of sugar cane.[33,34] Molasses are used for different purposes in various sectors, for example, as an additive in the production of alcohol, citric acid, animal feed, medicine, cement based mortar, and asphalt tar.[35] Thus, the above-mentioned materials can be considered as easily available low-cost raw materials that could be valorized in the production of composites.

It is known that wood-based and plant fiber polymer composite materials have low fire resistance.[36,37] In different experimental studies, it has been remarked that natural mineral-based materials, such as clay,[37] fly ash,[38] vermiculite,[39] boron,[40] fluoroborate,[41] glass powder,[42] dolomite, perlite and sepiolite,[43] have been used to improve the flame retardancy of wood-based composite materials. Since mineral materials are non-flammable, they act as flame-retardants. Mineral particles form a barrier between the flames and the wood particles/fibers, preventing the flames from spreading over the material.[37] Turkey holds ~73% of the world's boron ore reserves.[44] The most significant boron minerals in Turkey are tincal, ulexite and colemanite. During the processing of these minerals, a substantial quantity of waste is produced. The storage of these wastes in tailing dams results in environment and groundwater contamination.[45] Therefore, in this study, we investigated the effect of adding colemanite to the composite materials formulation on their flammability.

Farag *et al*.[46] investigated the production of particleboard using waste olive stones. In their study, the water absorption (WA) ratio was found to be ~6%, the thickness swelling (TS) ratio was ~18%, and the flexural strength value was ~15 MPa in the specimens prepared in 80/20 filler/binder (f/b) ratio. It was concluded that the produced composite material complies with the standards for indoor uses, and that waste olive stones can serve as an alternative source of raw material to replace wood and wood fiber materials. Yeniocak *et al*.[47] investigated the use of polyester fiber, fabric fiber and plaster mesh in composite materials produced from vine pruning stalks. Among 8 different mixtures, the highest mechanical properties were determined as TS value ~30%, flexural strength ~13 MPa, and

screw withdrawal strength ~17 N/mm^2 in composite specimens prepared using plaster mesh. Akinyemi *et al*.[48] investigated the production of particleboard using waste groundnut shells, waste rice husks, cassava starch, and UF. According to their experimental results, the best mechanical performance was obtained for particleboard specimens produced with 70% waste rice husk + 30% waste groundnut shell. In addition, it was stated that the use of cassava starch in the binder mixture of the particleboard specimens decreased the formaldehyde release values of the specimens. In another experimental study, Sahin *et al*.[15] investigated the use of peanut shell and glass powder in the production of polymeric composite materials. In their work, the optimum production conditions for achieve high flexural strength values were determined as filler/binder ratio of 3/1, moulding pressure of 2.72 MPa, and moulding temperature of 120 °C. On the other hand, it was determined that the use of 5% glass powder in the composite material production increased the LOI value of the material and the tensile strength decreased considerably as the glass powder ratio increased in the material mixture. Oktay *et al*.[9] investigated the production of wood-based composite boards with a binder mixture produced with different ratios of corn starch, tannin, and sugar mixture. It was detected that the bending strength value of the composite material generated in the study was ~11 MPa, the surface hardness was ~1.3 MPa, and the material belonged to P2 class according to EN 312 standard. In addition, the use of bio-based binder materials in the production of particleboards can significantly reduce formaldehyde emissions. Pirayesh and Khazaeian[49] investigated the use of waste almond shells in the production of composite materials. In their experimental study, it was stated that the most suitable mechanical test results were obtained when 30% waste almond shell was used, instead of sawdust. In composite materials prepared with a 30/70 almond shell/sawdust ratio, flexural strength was ~13 MPa, internal bond strength was 0.44 MPa, WA and TS (24 hours) values were ~56% and 12%, respectively. It was also concluded that the use of PF in composite material production improves the mechanical properties of the material.

The aim of this experimental study has been to investigate the feasibility of producing composite particleboard materials using waste plum pits. In the literature review, no previous study on the use of waste plum pits in the production of composite materials has been found.

EXPERIMENTAL

Materials

In this work, the formulation of particleboard composites was investigated with the addition of the following components: plum pits were used as filler material, industrial hemp fiber – to increase flexural strength, PVAc and sugar beet molasses – as binders, PF – to reduce the water absorption ratio of the specimens and prevent biodegradability, and waste colemanite – to improve the flame resistance properties.

Plum pits used in the production of composite specimens were obtained from the wholesale warehouse of the vegetable market in Eskişehir Province, Turkey. The density of the ground plum pit material was 0.84 g/cm^3. The sugar beet molasses used were taken from the waste molasses silos of the Eskişehir Sugar Factory in Turkey, in a plastic container. The chemical and physical properties of the molasses are given in Table 1. Hemp fibers were collected from a field in Kastamonu Province, Turkey. These fibers were cut with a knife to ~6 cm in length in the laboratory. PF was obtained from Polisan Chemical Factory in Kocaeli Province, Turkey, and PVAc was obtained from a glue factory in Eskişehir Province, Turkey. The mechanical and physical properties of PVAc and PF binder materials are given in Table 2. Waste colemanite was obtained from Emet Eti Boron Factory, located in Kütahya Province, Turkey. The chemical composition of waste colemanite is presented in Table 3. The density of waste colemanite was ~2.40 g/cm^3. Sulfuric acid was added to the composite specimen mixtures at the ratio of 0.10 mL as a hardening catalyst material. The density of sulfuric acid was 1.83 g/cm^3.

Methods

Preparation of test specimens

The waste plum pits were first dried in a drying oven at the temperature of 105 ± 5 °C. The pits were then ground with a Retsch grinder, and the ground material was sieved through 450 µm and 600 µm sieves. In the production of composite specimens, 450 µm upper sieved powder material and 600 µm lower sieved powder were used as fillers. Thus, composite specimens were produced with ground plum pits with an average particle size of $\bar{d}$: 525 µm.

A molasse-based binder mixture was used in the production of composite specimens. In a previous experimental study,[10] the most suitable molasse-based binder mixture for composite material production was determined as having the following composition: 45% PVAc, 35% molasses, and 20% PF by weight, and the same ratios were used in this study.

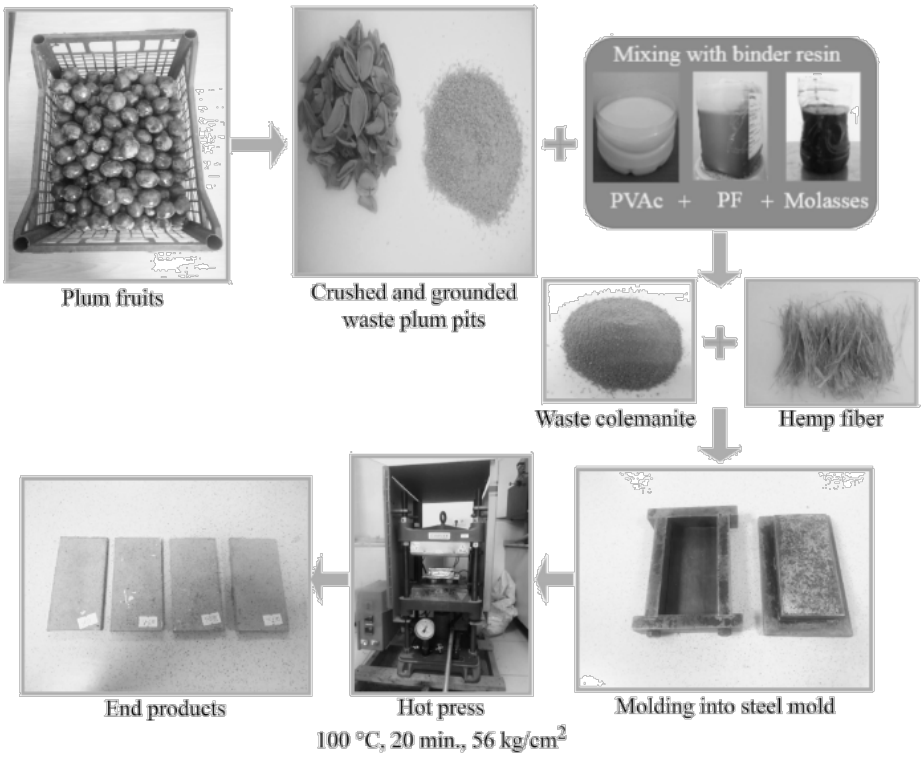

Figure 1: Composite specimen production process

Table 1
Chemical and physical properties of molasses (wt%)

Brix (%)	Purity (%)	Sucrose (%)	Ash (%)	Nitrogen (%)	Betaine (%)	Raffinose (%)	Invert sugar (%)	pH	Appearance	Density (g/cm^3)
86	59	52	11.9	1.90	5	1.10	0.09	9	Deep brown	1.178

Table 2
Mechanical and physical properties of PVAc and PF

Properties	PVAc	PF
Color	Milk white	Reddish tint
Solid (wt%)	~ 50	46 ~ 48
Density (g/cm^3)	1.19 ~ 1.21	1.20 ~ 1.21
pH	3.5 ~ 4	10.50 ~ 13.00
Viscosity (cPs, 20 °C)	-	300 ~ 700
Free formaldehyde (%)	-	< 0.1
Flow rate (s, DC4)	-	50 ~ 130
Gel time (min, 105 °C)	-	10 ~ 20
Water tolerance	-	Infinite

The production parameters of f/b, moulding pressure, and hemp fiber ratio were determined by trial and error in composite specimen production. All materials used in composite specimen production were weighed with precision scales. The filler and the binder were manually mixed with a metal rod in a plastic container for ~5 minutes. After determining the optimum f/b ratio, composite specimens were produced with a constant weight of 120 g. A steel mold with dimensions of 120×60 mm was used for composite specimen production, and the prepared mixture was carefully poured into this mold. The mixture poured into the steel mold was hot pressed at a temperature of 100 °C for 20 minutes with a Carver brand hot press device. The demolded specimens were cured in a drying oven at 70 °C for 24 hours. The specimen size produced was 120×60×(specimen thickness) mm. Specimen dimensions were measured with a precision caliper. The prepared specimens were kept in a laboratory environment at room temperature of 20±2 °C during the experimental studies. The production stages of the composite specimens are shown in Figure 1.

Testing methods

Three-point flexural strength

Three parameters were varied in the production of the composite specimens: f/b ratio, moulding pressure, and hemp fiber ratio. The optimum values of these parameters were determined according to three-point flexural strength test following EN 310[50] standard. The produced 120×60×(specimen thickness) mm sized specimens were saw cut to 60×15×(specimen thickness) mm dimensions for the three-point flexural strength test. A Shimadzu AG-I testing machine was used in the flexural strength test, the crosshead speed was set to 10 mm/min, and the span length was set to 40 mm. The three-point flexural strength values are the arithmetic average of six composite specimens. The specimen sizes were entered into the test machine's computer system. The maximum flexural strength values of the specimens were recorded from the computer-controlled data gathering system of the test machine.

Limiting oxygen index (LOI)

As in the previous experimental study,[10] waste colemanite was added into the composite formulation in quantities of 0%, 5%, 10%, 20%, 20%, 40% and 50% by weight, instead of plum pits, to improve the non-flammability of the composite specimens produced in the laboratory. The flammability of the composite specimens was determined by the imiting Oxygen Index (LOI) test. For the LOI test, composite specimens were cut to 100×10×(specimen thickness) mm according to ASTM D 2863-19[51] standard, and the LOI test was performed on a DYNISCO brand test device. Composite specimens were placed vertically in the glass chamber inside the test device. The flow of the oxygen/nitrogen gas mixture was provided in the glass chamber. The oxygen level was continuously increased, while the top part of the composite specimen was ignited for 30 seconds. The minimum oxygen level was recorded when a continuous flame was obtained in the composite specimens. The limiting oxygen index values are the arithmetic average of 10 composite specimens.

Table 3
Chemical composition of waste colemanite

Comp.	B_2O_3	SiO_2	CaO	Al_2O_3	MgO	K_2O	Fe_2O_3	SrO	TiO_2	SO_4	Na_2O	P_2O_5
(%)	34.5	23.6	18.6	9.71	8.84	1.66	1.41	1.10	0.23	0.21	0.13	0.01

Thickness swelling (TS) and water absorption (WA)

Thickness swelling (TS) and water absorption (WA) tests were performed on specimens prepared in 50×50×(specimen thickness) mm dimensions according to EN317[52] for 24 hours. The dried composite specimens were weighed, and their dry weights (m_1) were recorded. In addition, the thicknesses of the dry specimens (t_1) were measured in different points, and the thickness values of the dry specimens were recorded. Afterwards, the specimens were soaked in water at room temperature for 24 hours. After 24 hours, the specimens were taken out of the water. Wet specimens were weighed (m_2) and the thicknesses of wet specimens (t_2) were measured in different points. The thickness swelling values and water absorption ratio are the arithmetic averages of 12 specimens. The water absorption ratios of the specimens were calculated by using Equation (1):

$$\text{Water absorption ratio (\%)} = \left(\frac{m2-m1}{m1}\right) \times 100 \quad (1)$$

Also, the thickness swelling values of the specimens were calculated by using Equation (2):

$$\text{Thickness swelling value (\%)} = \left(\frac{t2-t1}{t1}\right) \times 100 \quad (2)$$

Screw withdrawal

The screw withdrawal holding strength test was performed with a Mares brand test device, using 50×50×(specimen thickness) mm sized specimens, following EN320.[53] In this experiment, a pilot hole was

first drilled in the center of the composite specimens for screw installation, and then a screw was installed in this pilot hole. Screw sizes were 4.2 mm in diameter and 38 mm in length. The thicknesses of the specimens were introduced into the testing machine's computer system. The screw withdrawal strength values of the specimens were recorded from the computer-controlled data gathering system of the test machine. The screw withdrawal strength values are the arithmetic average of 12 specimens.

RESULTS AND DISCUSSION

Filler/binder (f/b) ratio

Composite specimens were produced with waste plum pits with an average particle size ($\bar{d}$) of 525 µm at different f/b ratios (0.25, 0.375, 0.50, 0.75, 1.00 f/b ratio), keeping the amount of binder constant. The thicknesses of the specimens were measured as 6 mm, 6.1 mm, 6.3 mm, 7 mm, and 7.6 mm, respectively, depending on the increase in the filler ratio. The f/b ratio–flexural strength relation of the composite specimens is shown in Figure 2.

According to Figure 2, the maximum flexural strength value of the specimens produced with a 0.50 f/b ratio was detected as ~12 MPa. After this f/b ratio, the flexural strength values of the specimens reduced as the f/b ratio increased. This reduction can be explained by the weakening of the adhesion bonding between the binder and the increasing amount of filler particles in the mixture due to the constant quantity of binder. The experimental results determined in this study are compatible with others reported previously. Choi *et al*.[54] and Sahin *et al*.[15] stated that, beyond a specific f/b ratio, the flexural strength values of the specimens reduced as the amount of the filler increased. The f/b ratio of 0.50, where the maximum flexural strength (~12 MPa) was obtained, was detected as the most appropriate f/b ratio, and the f/b ratio of 0.50 was kept constant in the following stages of the study.

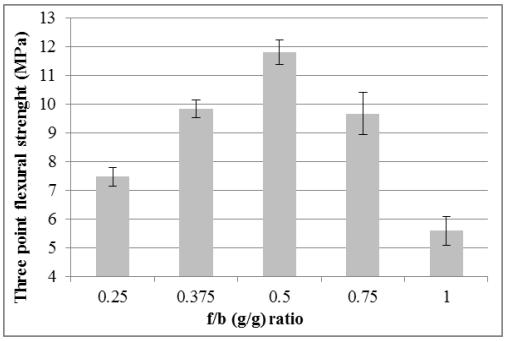

Figure 2: Relation between f/b ratio and flexural strength of composite specimens (starting production conditions: moulding pressure temperature: 100 °C, moulding pressure time: 20 min, and pressure: 49 kg/cm^2, binder amount: 80 g, $\bar{d}$: 525 µm)

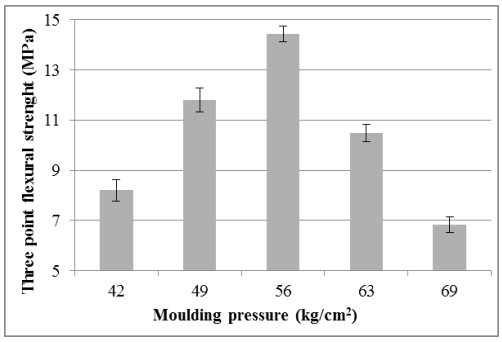

Figure 3: Relation between moulding pressure and flexural strength of composite specimens (production conditions: binder amount: 80 g, f/b: 0.50, moulding pressure temperature: 100 °C, moulding pressure time: 20 min, $\bar{d}$: 525 µm)

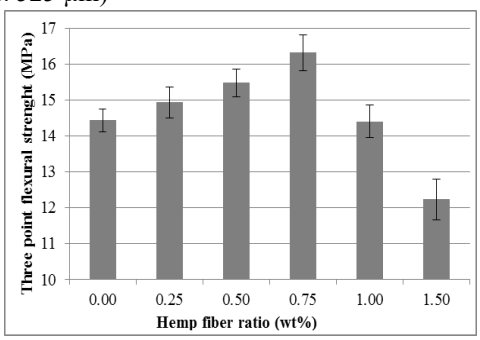

Figure 4: Relation between hemp fiber ratio and flexural strength of composite specimens (production conditions: binder amount: 80 g, f/b: 0.50, moulding pressure temperature: 100 °C, moulding pressure time: 20 min, moulding pressure: 56 kg/cm^2, $\bar{d}$: 525 µm)

Moulding pressure

Figure 3 shows the moulding pressure–flexural strength relation of composite specimens prepared by applying between 42 kg/cm^2 and 69 kg/cm^2 moulding pressure.

Depending on the moulding pressure value applied in composite specimen production, the specimens were obtained in different thicknesses. Accordingly, specimens with thicknesses of 6.4 mm, 6.2 mm, 6.1 mm, 6 mm, and 5.8 mm were produced for moulding pressure values of 42 kg/cm^2, 49 kg/cm^2, 56 kg/cm^2, 63 kg/cm^2, and 69 kg/cm^2, respectively. According to Figure 3, the maximum flexural strength value (~15 MPa) was obtained in the specimen produced with a 56 kg/cm^2 moulding pressure value. Up to 56 kg/cm^2 moulding pressure, the flexural strength values of the specimens increased, which can be explained by the better compression of the specimens in the mold, thus reducing the gaps in the specimen. At moulding pressures higher than 56 kg/cm^2, the relative leakage of the binder material out of the mold was observed. As a result of this leakage, it can be said that the flexural strength values of the specimens produced with high moulding pressure values reduced because of the reduction of the amount of binder in the mixture. Similarly, in our previous experimental study, it was found that the flexural strength values of composite specimens increased up to a specific moulding pressure value, beyond which the flexural strength values of the specimens decreased because of the leakage of binder material out of the mold.[10] As a result, the moulding pressure value of 56 kg/cm^2, where the maximum flexural strength was obtained, was selected as the most suitable moulding pressure value, and composite specimens were produced with this moulding pressure value in the next stages of the study.

Hemp fiber ratio

Composite specimens were produced by adding hemp fiber to the composite specimen mixtures in ratios of 0%, 0.25%, 0.50%, 0.75%, 1.00% and 1.50%, respectively, according to the amount of binder, and thus, it was aimed to increase the flexural strength of the specimens. Bassyouni and Hasan[55] stated in their study that the addition of natural fibers in composite materials improves the physical and mechanical properties of the materials. Figure 4 shows the relation between the hemp fiber ratio and flexural strength.

According to Figure 4, the maximum flexural strength value of the specimens with 0.75% hemp fiber was determined as ~16 MPa, being ~13% higher than that of the plain specimens. The reduction in the flexural strength values of the specimens produced using higher ratios of hemp fiber can be explained by the gaps formed around the fiber. Similarly, Narciso *et al*.[56] found that the flexural strength values of the specimens reduced because of the gaps formed in the specimen due to the increase in the fiber ratio in the composite specimen. Shibata *et al*.[57] determined that the flexural strength values of the specimens prepared by adding fiber up to a specific ratio increased. The experimental results in the literature are consistent with this experimental study. The ratio of 0.75%, where the maximum flexural strength was obtained, was considered as the most suitable hemp fiber ratio. The specimens produced in the later stages of the study were obtained using a constant 0.75% hemp fiber ratio.

TS and WA

The TS and WA values of the composite specimens produced using different ratios of hemp fiber between 0 and 1.50% are shown in Figure 5 and Figure 6, respectively.

When both Figure 5 and Figure 6 were examined, it was determined that the TS and WA values of the composite specimens increased as the hemp fiber ratio increased. These increases in TS and WA values can be explained by the formation of more gaps around the fibers in the specimen with higher hemp fiber ratios, which were filled with water. In addition, generally, natural fibers are hygroscopic due to chemical components such as hemicelluloses and lignin.[58] In this case, due to the water absorption of hemp fibers, the TS value and WA ratio of the composite specimens also increased. Similar results were observed by Kiani *et al*.[59] and Zuraida *et al*.[60]

Accordingly, the maximum WA and TS values were determined for specimens with 1.50% hemp fiber. In the composite specimens with 0.75% hemp fiber, where the maximum flexural strength was obtained, the TS value was ~4.6%, and the WA value was ~18.7%. According to EN 312[61] standard for particleboards, composite specimens with 0.75% hemp fibers are suitable for P3, P4, and P5 composite board classes in terms of TS value.

Limiting oxygen index (LOI) value

The lowest oxygen (O_2) concentration value required for a material to sustain burning is called the limiting oxygen index (LOI). Easy-burning materials have lower LOI values (≤28%), while difficult-burning materials have higher LOI values (≥28%).[43] The objective of the experimental study was to increase the LOI values of the composite specimens by incorporating waste colemanite into the mixture to impart non-flammability to the specimens. Figure 7 shows the LOI value–waste colemanite relation of composite specimens prepared by substituting waste colemanite for plum pits in the specimen mixtures in various ratios between 0 and 50 wt%.

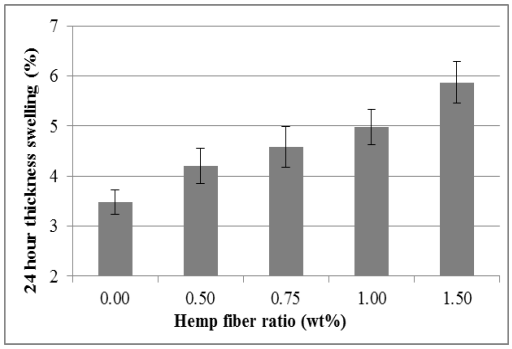

Figure 5: Relation between hemp fiber ratio and TS value of composite specimens (production conditions: binder amount: 80 g, f/b: 0.50, moulding pressure temperature: 100 °C, moulding pressure time: 20 min, moulding pressure: 56 kg/cm^2, $\bar{d}$: 525 µm

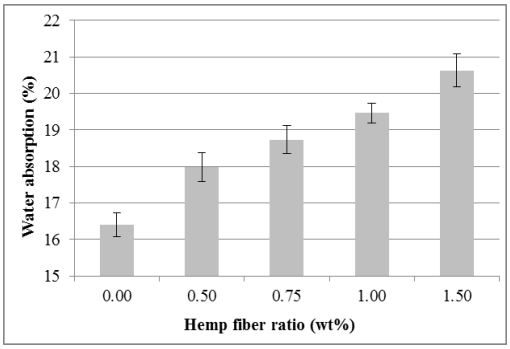

Figure 6: Relation between hemp fiber ratio and WA value of composite specimens (production conditions: binder amount: 80 g, f/b: 0.50, moulding pressure temperature: 100 °C, moulding pressure time: 20 min, moulding pressure: 56 kg/cm^2, $\bar{d}$: 525 µm)

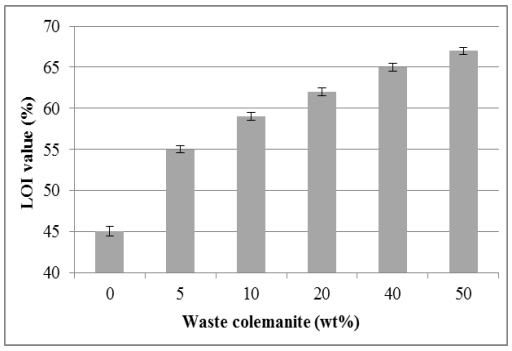

Figure 7: Relation between waste colemanite ratio and LOI value of composite specimens (production conditions: binder amount: 80 g, f/b: 0.50, moulding pressure temperature: 100 °C, moulding pressure time: 20 min, moulding pressure: 56 kg/cm^2, $\bar{d}$: 525 µm, hemp fiber: 0.75%)

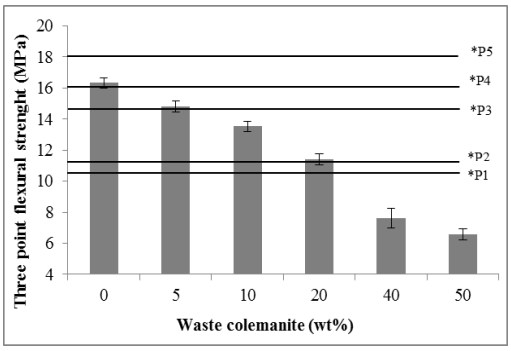

Figure 8: Flexural strength as a function of colemanite ratio (production conditions: binder: 80 g, f/b: 0.50, moulding pressure: 56 kg/cm^2 at 100 °C for 20 min, $\bar{d}$: 525 µm, hemp fiber: 0.75%); EN312 flexural strength limit values: *P1≥10.5 MPa (general use), *P2≥11 MPa (interior use), *P3≥15 MPa (wet-non load bearing), *P4≥16 MPa (dry-load bearing), *P5≥18 MPa (wet-load bearing)

When Figure 7 is examined, it is seen that the LOI values of the specimens increase as the waste colemanite content increases in the specimen mixtures. This increase can be explained by the fact that waste colemanite is a non-flammable mineral material. The maximum LOI value was obtained from the specimens with 50% colemanite. The LOI value of the specimens with 50% colemanite is ~49% higher than the LOI value of the specimens with 0% colemanite. Similarly, in different studies, it was found that the LOI values of the specimens increased when boron powder, sepiolite, dolomite, and perlite minerals were used in the production of composite specimens.[40,43] Accordingly, the LOI values obtained are similar to those reported in the literature. According to the experimental results, the waste colemanite used improved the non-flammability of the specimens.

On the other hand, the flexural strength values of the composite specimens produced using waste colemanite were compared with the flexural strength limit values of EN 312[61] particleboard-specifications standard. Figure 8 shows the flexural strength limit values of EN 312 standard together with the waste colemanite–flexural strength relation. As can be seen in Figure 8, the flexural strength of the composite specimens reduces as the waste colemanite content increases. This reduction in flexural strength can be explained by the fact that waste colemanite particles form a weaker polymer bond with the binder material. Similar results were found in studies where waste glass powder[42] and vermiculite[39] were used in the production of composite materials. Accordingly, the experimental results obtained from previous scientific studies and those of this study are in agreement. On the other hand, in terms of EN 312[61] standard, the minimum flexural strength limit value of P1 class particleboards for general use with a thickness of 6~13 mm is 10.5 MPa. When Figure 8 is examined, it is seen that polymer composite particleboard materials produced by adding up to 20% waste colemanite are suitable for both P1 and P2 classes according to their flexural strength values. However, the flexural strength values of the specimens prepared using 40% and 50% waste colemanite could not be categorized because they were lower than the minimum flexural strength limit value established by EN 312[61] standard.

Screw withdrawal strength

The screw holding capacity of composite materials plays an especially important role in the construction industry and various application areas.[12] In this study, the effect of using waste colemanite in polymer composite particleboard production on the screw withdrawal strength of the specimens was determined. Figure 9 shows the set-up of the screw withdrawal experiment. Figure 10 shows the waste colemanite ratio–screw withdrawal strength relation in composite specimens.

When Figure 10 is examined, the maximum screw withdrawal strength (~39 N/mm) was obtained in the specimens prepared using 5% colemanite. According to the flexural strength, the screw withdrawal strength of the specimens prepared using 20% colemanite, which is in P1 class, was determined as ~31 N/mm. The lowest screw withdrawal strength (~19 N/mm) was found in specimens prepared using 50% colemanite. In addition, Figure 10 shows that the screw withdrawal strength of the specimens reduces as the waste colemanite content in the composite specimen increases. The reduction in both screw strength and flexural strength values of composite specimens can be explained by the weak adhesive bonding of colemanite particles with the binder material. Similarly, in another scientific work, it was reported that the screw withdrawal and flexural strength values of the specimens prepared by adding calcite minerals to the composite specimen mixtures reduced in parallel.[62]

Figure 9: Screw withdrawal experiment

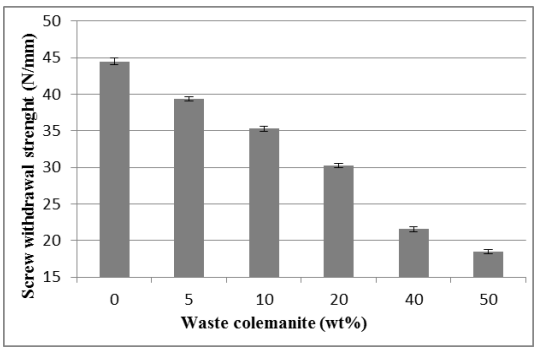

Figure 10: Screw withdrawal strength as a function of colemanite ratio (production conditions: binder: 80 g, f/b: 0.50, moulding pressure: 56 kg/cm^2 at 100 °C for 20 min, $\bar{d}$: 525 μm, hemp fiber: 0.75%)

Table 4
Optimum production conditions and waste material ratios according to experimental results

Production conditions	Unit	Value
f/b	(g/g)	0.50
Moulding pressure	(kg/cm^2)	56
Hemp fiber	(%)	0.75
Waste colemanite	(wt%)	up to 20

Table 5
Comparison of experimental data with other research results

Authors	Waste plant materials	Binder types	Flexural strength (MPa)	WA (24 h) (%)	TS (24 h) (%)	Screw withdrawal strength (N/mm)	LOI (%)
Şahinöz *et al*.[10]	Pine cone	Molasses+PF+PVAc	17.4	16.4	4.8	41.6	55
Özdemir[43]	Wood fibers	UF	17.3	114.9	46.9	-	27.7
Farag *et al*.[46]	Olive stone	Polyester liquid resin	15.6	6.4	18.2	-	-
Yeniocak *et al*.[47]	Vine pruning	UF	3.5~13.6	-	12.5~30.8	10.5~17.7	-
Pirayesh *et al*.[49]	Almond shell	UF	13.4	56.6	12.3	-	-
Biswas *et al*. [63]	Bamboo	UF	15.7	47.9	16.5	-	-
This study	Plum pits	Molasses+PF+PVAc	11.4~16.3	18.7	4.6	30.2~44.5	45~61

In this study, various eco-friendly composite materials were manufactured using plum pits, hemp fiber, molasses, and waste colemanite. Table 4 summarizes the optimum production conditions and plant waste material ratios, as determined by the experimental studies.

In Table 5, the experimental data obtained from this experimental study are compared with the results of other previously reported studies in the literature. In Table 5, the experimental results of composite materials produced with various plant waste materials and different binding materials obtained from the literature are given. Examining the data, it can be concluded that the mechanical properties of the composite materials produced in this study are generally more suitable for application, compared to others.

CONCLUSION

This study focuses on the utilization of industrial plant waste in the production of composite particleboard, while seeking solutions for avoiding the disadvantages of plant-based composite materials. Thus, composite particleboards were produced by using waste plum pits. The optimum moulding pressure in composite material production was found to be 56 kg/cm^2. According to the flexural strength, the optimum f/b ratio was determined as 0.50.

Also, hemp fiber increased the flexural strength of composite materials. The optimum hemp fiber ratio in the composite particleboard material mixture was found to be 0.75%. The addition of hemp fiber in the production of composite materials relatively increased the WA and TS values of the materials. In addition, it has been determined that waste colemanite increases the LOI value by improving the non-flammability of composite materials. However, waste colemanite reduces the flexural strength and screw withdrawal strength of polymer composite particleboards.

To conclude, waste plum pits can be used as an alternative filler material, instead of wood chips, in the production of polymer composite materials. Polymer composite materials produced under the above-mentioned conditions using up to 20% waste colemanite can be used as environment-friendly building materials in indoor and outdoor spaces, as they are classified as P1 and P2 according to EN 310.

It is anticipated that utilizing plant wastes in the production of composite materials will protect forests, reduce environmental pollution, and lower production costs. Due to the use of sugar beet molasse-based binder material in the study, the formaldehyde emission of the produced material is estimated to be quite low.

REFERENCES

[1] N. A. A. Aziz, M. Mohamed, M. Mohamad, M. H. M. Amini, M. Abdul *et al*., *ARPN J. Eng. Appl. Sci*., **10**, 376 (2015)

[2] P. Chaowana, *J. Mater. Sci. Res*., **2**, 90 (2013), http://dx.doi.org/10.5539/jmsr.v2n2p90

[3] M. Risholm-Sundman and E. Vestin, *Holz. Roh Werkst*., **63**, 179 (2005), https://doi.org/10.1007/s00107-004-0549-z

[4] P. Solt, J. Konnerth, W. Gindl-Altmutter, W. Kantner, J. Moser *et al*., *Int. J. Adhes. Adhes*., **94**, 99 (2019), https://doi.org/10.1016/j.ijadhadh.2019.04.007

[5] W. Gao, G. Du and D. P. Kamdem, *Polym. Compos*., **37**, 949 (2016), https://doi.org/10.1002/pc.23254

[6] S. W. Kariuki, J. Wachira, M. Kawira and G. Murithi, *J. Chem*., **2019**, 1 (2019), https://doi.org/10.1155/2019/5256897

[7] J. Chrobak, J. Iłowska and A. Chrobok, *Molecules*, **27**, 4862 (2022), https://doi.org/10.3390/molecules27154862

[8] C. Kumar and W. Leggate, *Int. J. Adhes. Adhes*., **118**, 103187 (2022), https://doi.org/10.1016/j.ijadhadh.2022.103187

[9] S. Oktay, N. Kızılcan and B. Bengü, *Ind. Crop. Prod*., **170**, 113689 (2021), https://doi.org/10.1016/j.indcrop.2021.113689

[10] M. Şahinöz, H. Y. Aruntaş and M. Gürü, *Case Stud. Constr. Mater*., **16**, e01013 (2022), https://doi.org/10.1016/j.cscm.2022.e01013

[11] K. Rohit and S. Dixit, *Polym. Renew. Resour*., **7**, 43 (2016), https://doi.org/10.1177/204124791600700202

[12] A. Bektas, C. Guler, H. Kalaycioğlu, F. Mengeloglu and M. Nacar, *J. Compos. Mater*., **39**, 467 (2005), https://doi.org/10.1177/0021998305047098

[13] L. Teuber, V. S. Osburg, W. Toporowski, H. Militz and A. Krause, *J. Clean. Prod*., **110**, 9 (2016), https://doi.org/10.1016/j.jclepro.2015.04.009

[14] S. Jena and R. Singh, *Environ. Res*., **206**, 112284 (2022), https://doi.org/10.1016/j.envres.2021.112284

[15] I. Sahin, H. M. Tasdemir, A. F. Karabulut and M. Gürü, *Arab. J. Sci. Eng*., **42**, 1559 (2017), https://doi.org/10.1007/s13369-017-2427-0

[16] Abolaji, O. Adeyinka and A. Olaitan, *Am. J. Eng. Res*., **6**, 314 (2017)

[17] M. Núñez-Decap, A. Wechsler-Pizarro and M. Vidal-Vega, *Sustain. Mater. Technol*., **29**, e00300 (2021), https://doi.org/10.1016/j.susmat.2021.e00300

[18] U. D. Idris, V. S. Aigbodion and C. U. Atuanya, *Tribol. Ind*., **33**, 173 (2011)

[19] H. M. Tasdemir, A. Sahin, A. F. Karabulut and M. Gürü, *Cellulose Chem. Technol*., **53**, 517 (2019), https://doi.org/10.35812/CelluloseChemTechnol.2019.53.52

[20] G. Nemli, H. Kırcı, B. Serdar and N. Ay, *Ind. Crop. Prod*., **17**, 39 (2003), https://doi.org/10.1016/S0926-6690(02)00057-2

[21] H. T. Sahin and M. B. Arslan, *Sci. Eng. Compos. Mater*., **20**, 337 (2013), https://doi.org/10.1515/secm-2012-0033

[22] A. Taha, M. S. Elkafafy and H. El Mously, *Ain Shams Eng. J*., **9**, 1457 (2018), https://doi.org/10.1016/j.asej.2016.10.003

[23] M. C. Wong, S. I. Hendrikse, P. C. Sherrell and A. V. Ellis, *Waste Manag*., **118**, 501 (2020), https://doi.org/10.1016/j.wasman.2020.09.007

[24] S. Tangjuank, *Int. J. Phys. Sci*., **6**, 4528 (2011), https://doi.org/10.5897/IJPS11.1057

[25] L. K. Jawad, A. A. Beddai, M. A. Nasser and M. K. Mejbel, *Mater. Today Proc*., **57**, 980 (2022), https://doi.org/10.1016/j.matpr.2022.03.396

[26] J. Wang, Y. Hu, *Waste Biomass Valoriz*., **7**, 1447 (2016), https://doi.org/10.1007/s12649-016-9523-3

[27] R. S. F. Martins, F. G. Goncalves, P. G. de Alcântara Segundinho, R. C. C. Lelis, J. B. Paes *et al*., *J. Build. Eng*., **43**, 102903 (2021), https://doi.org/10.1016/j.jobe.2021.102903

[28] K. Ucar, G. Oruk and S. Engindeniz, *Sarhad J. Agric*., **38**, 409 (2022), https://dx.doi.org/10.17582/journal.sja/2022/38.2.409.416

[29] T. Miloševic, N. Miloševic and I. Glisic, *J. Soil Sci. Plant Nutr*., **13**, 706 (2013), http://dx.doi.org/10.4067/S0718-95162013005000056

[30] E. M. Salentijn, Q. Zhang, S. Amaducci, M. Yang and L. M. Trindade, *Ind. Crop. Prod*., **68**, 32 (2015), https://doi.org/10.1016/j.indcrop.2014.08.011

[31] K. Wielgusz, M. Praczyk, L. Irzykowska and D. Świerk, *Ind. Crop. Prod*., **175**, 114245 (2022), https://doi.org/10.1016/j.indcrop.2021.114245

[32] G. D. Najafpour and C. P. Shan, *Bioresour. Technol*., **86**, 91 (2003), https://doi.org/10.1016/S0960-8524(02)00103-7

[33] H. Zaki Dizaji, S. Haroni, M. J. Sheikhdavoodi, S. M. Safieddin Ardebili, M. González Alriols *et al*., *Energ. Sources A*: *Recovery Util. Environ. Eff*., **1**, 1 (2021), https://doi.org/10.1080/15567036.2021.1898493

[34] L. Jamir, V. Kumar, J. Kaur, S. Kumar and H. Singh, *Environ. Technol. Rev*., **10**, 131 (2021), https://doi.org/10.1080/21622515.2021.1892203

[35] S. Solomon, *Sugar Tech*., **13**, 408 (2011), https://doi.org/10.1007/s12355-011-0114-0

[36] M. Gürü, A. F. Karabulut, M. Y. Aydın and İ. Bilici, *High Temp. Mater. Proc*., **34**, 599 (2015), https://doi.org/10.1515/htmp-2014-0092

[37] K. C. Kouadio, B. Traoré, S. P. Kaho, C. H. Kouakou and E. Emeruwa, *Open J. Appl. Sci*., **10**, 834 (2020), https://doi.org/10.4236/ojapps.2020.1012059

[38] M. Rajendran and C. K. Nagarajan, *J. Nat. Fibers*, **19**, 4557 (2022), https://doi.org/10.1080/15440478.2020.1867943

[39] M. Ghofrani, A. Ashori and R. Mehrabi, *Polym. Test*., **60**, 153 (2017), https://doi.org/10.1016/j.polymertesting.2017.03.028

[40] E. D. Tomak and A. D. Cavdar, *Thermochim*. *Acta*, **573**, 181 (2013), https://doi.org/10.1016/j.tca.2013.09.022
[41] Y. D. Aydın, M. Gürü and M. Akkurt, *Cellulose Chem*. *Technol*., **55**, 893 (2021), https://doi.org/10.35812/CelluloseChemTechnol.2021.55.75
[42] F. Pahlevani and V. Sahajwalla, *J*. *Clean*. *Prod*., **195**, 215 (2018), https://doi.org/10.1016/j.jclepro.2018.05.205
[43] F. Özdemir, *BioResources*, **14**, 2277 (2019), https://doi.org/10.15376/biores.14.1.2277-2286
[44] Eti Maden, Boron in the world, (accessed 24 November 2022), https://www.etimaden.gov.tr/en/eti-maden
[45] U. K. Sevim, *Mater*. *Struct*., **44**, 187 (2011), https://doi.org/10.1617/s11527-010-9618-4
[46] E. Farag, M. Alshebani, W. Elhrari, A. Klash and A. Shebani, *J*. *Build*. *Eng*., **29**, 101119 (2020), https://doi.org/10.1016/j.jobe.2019.101119
[47] M. Yeniocak, O. Göktaş, E. Özen and A. Gecgel, *Wood Res*., **61**, 265 (2016)
[48] A. Akinyemi, T. E. Kolajo and O. Adedolu. *Clean Techn*. *Environ*. *Policy*, **24**, 1653 (2022), https://doi.org/10.1007/s10098-021-02270-1
[49] H. Pirayesh and A. Khazaeian, *Compos*. *B Eng*., **43**, 1475 (2012), https://doi.org/10.1016/j.compositesb.2011.06.008
[50] European Norm EN 310, Wood based panels, determination of modulus of elasticity in bending and bending strength (1993)
[51] ASTM 2863–19, Standard test method for measuring the minimum oxygen concentration to support candle-like combustion of plastics (Oxygen Index) (2019)
[52] European Norm EN 317, Particleboards and fibreboards determination of swelling in thickness after immersion in water (1993)
[53] European Norm EN 320, Particleboards and fibreboards – determination of resistance to axial withdrawal of screws (2011)
[54] N. W. Choi, I. Mori and Y. Ohama, *Waste Manag*., **26**, 189 (2006), https://doi.org/10.1016/j.wasman.2005.05.008
[55] M. Bassyouni, S. W. U. Hasan, in "Biofiber Reinforcements in Composite Materials", Woodhead Publishing, 2015, pp. 385-422, https://doi.org/10.1533/9781782421276.4.385
[56] R. P. Narciso, A. H. S. Reis, J. F. Mendes, N. D. Nogueira and R. F. Mendes, *Waste Biomass Valoriz*., **12**, 1647 (2021), https://doi.org/10.1007/s12649-020-01099-x
[57] S. Shibata, Y. Cao and I. Fukumoto, *Polym*. *Compos*., **26**, 689 (2005), https://doi.org/10.1002/pc.20140
[58] I. Sabziparvar, L. Boulos and M. R. Foruzanmehr, *Environ*. *Technol*. *Innov*., **28**, 102930 (2022), https://doi.org/10.1016/j.eti.2022.102930
[59] H. Kiani, A. Ashori and S. A. Mozaffari, *Polym*. *Bull*., **66**, 797 (2011), https://doi.org/10.1007/s00289-010-0381-z
[60] I. Zuraida, T. Maisarah and W. M. Y. Wan-Shazlin-Maisarah, *J*. *Trop*. *For*. *Sci*., **29**, 485 (2017), https://doi.org/10.26525/jtfs2017.29.4.485492
[61] European Norm EN 312, Particleboards specifications (2010)
[62] I. Camlibel and M. Akgul, *Wood Res*., **65**, 231 (2020), https://doi.org/10.37763/wr.1336-4561/65.2.231244
[63] D. Biswas, S. K. Bose and M. M. Hossain, *Int*. *J*. *Adhes*. *Adhes*., **31**, 84 (2011), https://doi.org/10.1016/j.ijadhadh.2010.11.006