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Production and Characterization of Wood Polystyrene Composite Filled with Glass Fiber (GF) and Medium Density Fiber Board Dust (MF)

Cam Elyaf (GF) ve Orta Yoğunluklu Lif Levha Tozu (MF) ile Dolgulu Ahşap Polistiren Kompozit Üretimi ve Karakterizasyonu

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Abstract

In this study, it was aimed to recycle waste polystyrene (PS) to obtain PS composite with high screw withdrawal strength that can be used in the core layer of composite wood sandwich panels. For this purpose, waste MDF dust (MF) and glass fiber (GF) were used as fillers in the PS matrix. Waste PS was first dissolved in gasoline and then 50-100-150 % fillers were added and mixed. The solvent in the composite was removed from the composite with two different temperatures. Thickness swelling (TS) and water uptake (WA) amounts of the samples and screw withdrawal strength (SR) were analyzed for mechanical characterization. According to the analysis results, it was determined that as the MF ratio increased, there was no significant change in the TS, but the WA increased. MF filled composites has more TS than GF filled composites. However, it was determined that the WA in GF filled composites was higher than in MF filled composites. The fillers increased the densities except for the addition of 150% GF. SR analysis results showed that the addition of filler increased the SR of composites. As a result, waste PS can be converted into a material with high screw withdrawal strength by adding waste MF and GF and can be used instead of wood material.

Keywords: Polystyrene, Recycle, Waste, Glass fiber, MDF dust

Özet

Bu çalışmada atık polistirenin (PS) geri dönüştürülerek kompozit ahşap sandviç panellerin çekirdek tabakasında kullanılabilen, vida tutma direnci yüksek PS kompozit elde edilmesi amaçlanmıştır. Bu amaçla PS matrisinde dolgu maddesi olarak atık MDF tozu (MF) ve cam elyafı (GF) kullanılmıştır. Atık PS önce benzin kullanılarak eritilmiştir ve ardından % 50-100-150 oranında dolgu maddesi ile karıştırılmıştır. Kompozitteki çözücü iki farklı sıcaklık ile kompozitten uzaklaştırılmıştır. Numunelerin kalınlığına şişme (TS) ve su alma (WA) miktarları ile mekanik karakterizasyon için vida çekme dirençleri (SR) analiz edilmiştir. Elde edilen sonuçlara göre MF dolgusu arttıkça TS miktarında önemli bir değişiklik olmadığı ancak WA miktarının arttığı belirlenmiştir. GF dolgulu kompozitlerde MF'ye göre daha az kalınlığına şişme tespit edilmiştir. Ancak GF dolgulu kompozitlerde WA miktarının, MF dolgusuna göre daha fazla olduğu belirlenmiştir. % 150 GF ilavesi hariç dolgu maddeleri yoğunlukları arttırmıştır. Dolgu maddesi ilavesiyle SR artmıştır. Sonuç olarak atık PS, atık MF ve GF eklenerek yüksek vida tutma direncine sahip bir malzemeye dönüştürülebilir ve ahşap malzeme yerine kullanılabilir.

Anahtar Kelimeler: Polistiren, Geri dönüşüm, Atık, Cam elyafı, MDF tozu

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1. Introduction

The growing human population has led to greater interaction between humans and nature (Şahin, 2020), resulting in an increased demand for forest products (Kelleci et al., 2022). The increasing demand for timber has led to both rising wood prices and increased pressure on forest resources. This situation has made it necessary to use wood raw materials more efficiently and to evaluate wood residues. The need for sustainable and cost-effective solutions has led to an increase in research and development in this field. For this purpose, various wood composites have been produced (Ogundipe et al., 2021; Pham Van et al., 2021), which are currently used in the furniture industry (Smardzewski and Kramski, 2019; Roziņš et al., 2020; Wang et al., 2022).

In the furniture sector, lightweight panels are preferred. High-density panels cannot be used for ceiling and wall elements where both lightness and strength are important. Especially in the aviation, maritime, and aerospace industries, lightweight is an important issue in the manufacture of cabin cabinets. Various lightweight honeycomb panels have been produced for use in these industries (Khojasteh-Khosro et al., 2020, 2022; Jivkov et al., 2021). Lightweight and durable materials similar to aluminum are used in the core layer of these panels (Palomba et al., 2022; Shao et al., 2021; Uğur et al., 2020). These products are known as wood sandwich panels (WSP). Although these panels provide the desired lightness and strength, they are difficult to assemble because they have weak screw withdrawal strength (SR). Special fasteners are used to join the panels (Petutschnigg et al., 2004; Petutschnigg and Ebner, 2007; Heimbs and Pein, 2009; Smardzewski et al., 2017), making cabinet manufacturing both expensive and challenging.

The increase in wood prices in the world has forced manufacturers to produce wood-plastic mixture (WPC) products. WPC made of wood flour and thermoplastic(s) such as polyethylene (PE), polypropylene (PP), or polystyrene (PS) (Najafi et al., 2007; Adhikary et al., 2008; Birinci, 2023; Nelson et al., 2023). These materials have gained popularity because of their low-maintenance, sustainable alternative to traditional wood decking, fencing, and cladding materials (Friedrich and Luible, 2016; Agarwal and Gupta, 2017; Saba et al., 2017; Partanen and Carus, 2019). Wood and plastic combination results that is resistant to decay, rot, and insect damage (Morrell et al., 2006; Schirp et al., 2008), while also being lightweight and easy to install (Santoni et al., 2018). WPCs have become a viable solution for the construction industry seeking to reduce its environmental impact and increase sustainability (Akadiri et al., 2012). WPCs have become popular due to three main reasons. Firstly, they

are environmentally sustainable and often made from recycled materials, providing an eco-friendly alternative to traditional wood products (Osburg et al., 2016; Teuber et al., 2016; Elsheikh et al., 2022). Secondly, they require minimal maintenance cost compared to wood, making them a convenient and low-maintenance option for both residential and commercial use (Schwarzkopf and Burnard 2016; Patel and Rawat, 2017). Their durability and versatility make them a viable option for a range of applications, offering builders and designers a cost-effective and long-lasting solution for their projects (Silva, 2013; Rubino et al., 2020; H.-M. Wang et al., 2021).

Although access to wood materials has become difficult, access to plastic materials has both increased and become easier. (Rahimi and García, 2017; Eitzen et al., 2020). However, the production and disposal of plastic waste have led to significant environmental challenges and harm to marine life (Al-Thawadi, 2020). Data from the United Nations environmental program indicates that only a small percentage of plastic waste is recycled in Sub-Saharan Africa, while the rest is dumped in open areas or landfills, exacerbating waste management issues (Adeniran et al., 2022). Today, EPS (expanded polystyrene) is one of the most widely used thermoplastics that cause the most environmental pollution (Kehinde et al., 2020; Tapia-Blácido et al., 2022).

EPS is a synthetic polymer made from petroleum and widely used in packaging, insulation materials, and disposable coffee cups. However, EPS is not biodegradable and poses a significant environmental pollution risk when disposed of in landfills. EPS (Figure 1) and other polystyrene derivatives are persistent in the environment, making proper waste management and recycling essential to mitigate their negative impact (Chaukura et al., 2016).

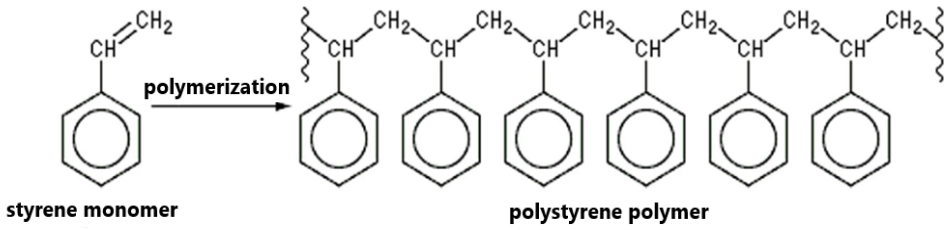

Figure 1. Polystyrene chemical formula (Adeniyi et al., 2022).

There are three methods of recycling polystyrene: mechanical, chemical, and thermal recycling. Mechanical recycling involves the use of machines to reduce the the volume of waste PS, while chemical recycling involves reducing waste PS to its monomer or solution using suitable solvents. Thermal recycling involves subjecting waste PS to high-temperature

heating to cause a breakdown of long-chain hydrocarbons (Schyns and Shaver, 2021; Ugwu and Obele, 2023).

Chemical recycling of EPS involves the use of various chemicals to dissolve EPS for subsequent applications. Solvent treatments such as dibasic esters, gasoline, d-limonene, and dialkyl carbonates have been used to reduce EPS. Chemical recycling has advantages such as high recycling efficiency, low energy requirement, and the discovery of post-consumer applications (Noguchi et al., 1998; Maharana et al., 2007; Vilaplana et al., 2007; Osemeahon et al., 2013). Recycled PSs are often used in the production of wood plastic composites.

WPCs made from polystyrene and wood flour are generally produced by twin screw extruders according to thermal method. In the literature, almost all the wood-plastic composites produced using polystyrene were produced by a twin-screw extruder. In some studies, which polystyrene is melted using solvents such as acetone and used in the production of wood/polystyrene composites, analysis samples were produced using either an extruder or a press mold. These studies are mentioned below.

In some wood plastic studies using acetone, Eskander et al. (2018) developed a hard wood–polymer composite (HWC) using rice straw waste and chemically recycled polystyrene foam by using acetone. Chun et al. (2019) studied the use of post-consumer polystyrene foam waste to create a WPC by blending recycled polystyrene with durian husk fiber and a processing aid. Kaho et al. (2020) aimed to repurpose EPS waste by developing a composite material with wood waste. The researchers created a resin from the EPS by dissolving it in acetone, which was then used as a binder to stabilize the samples. Koay et al. (2018) melted waste Polystyrene using acetone and produced analysis samples using a twin-screw extruder. Also, in some studies, different methods were used to prepare the analysis samples by which polystyrene was melted using acetone. In some studies, the adhesion resistance of melted PS to the surfaces of different materials was investigated (Maldas et al., 1988; Ponomarenko et al., 2020; Šernek et al., 2020; Sitorus et al., 2020; Sriprom et al., 2022; Osemeahon et al., 2022).

In this study, it is aimed to recycle PS, an industrial waste, with waste MF and GF fillers into a composite material with high SR and high physical properties. The PS composite produced for this purpose can be used in the core layer of WSP with its properties. Thus, it will be possible to produce more environmentally friendly products using industrial waste materials. The products can be used in the aviation, maritime and space industries due to their lightweight, high mechanical and environmentally friendly properties.

2. Material and Method

2.1 Material

Polystyrene (PS) material was collected from Bolu province. After the collected waste PS was separated from foreign materials, it was manually cut into 10 cm x 10 cm pieces by a knife. Collected polystyrene densities were around 10-20 kg/m^3. Polystyrene, widely utilized in various applications, offers transparency and colorability. It behaves as a thermoplastic, solidifying at room temperature. Its general formula is shown as $(C_8H_8)n$. Its density is around 1004 kg/m^3. The melting point is 240 °C and the glass transition point 100 °C. Waste medium-density fiber dust (MF) and glass fiber (GF) were used as fillers in PS. GF was purchased from the online market. Generally, GF is used in many areas such as adding volume and strength to the product and providing or increasing insulation in the Manufacturing Industry and Chemical Industry. In this study, GF was used to provide volume and durability to the PS composite. GF density was 900-950 kg/m^3, white color, and 0.25-0.75 microns.

MF was obtained by collecting the cutting residue dust from the furniture production workshops. The humidity of the collected MF was measured as 8 % according to Equation 1. The particle size of the MF is given in Table 1. Gasoline was used as a solvent. Unleaded gasoline was purchased from a local gas station.

$$MC(\%) = \frac{M_h - M_0}{M_0}\ x\ 100 \qquad (1)$$

M_h: Wet-weight (g),

M_0: Dry-weight (g),

MC: Moisture content (%)

Table 1. Screened MF fractional analyses.

Size (mm)	Weight (g)	Rate (%)
2 x 2	485	14
1 x 1	422	12
0.8 x 0.8	420	12
0.5 x 0.5	380	11
0.4 x 0.4	445	13
0.3 x 0.3	430	12
0.2 x 0.2	420	12
0.1 x 0.1	415	12
0.1 >	120	3

2.2 Method

PS was cleaned of foreign matter (Figure 2a) and melted in a container using gasoline solvent (Figure 2b). Gasoline was used at the rate of 1 kg/1 liter to melt PS. The mixing ratios used in the analysis samples are given in Table 2. PSs were mixed with the fillers in the same container in the amounts given in Table 2. Mixing was done manually for 10 minutes with a metal spatula and then shaped by hand (Figure 2c). After the mixture reached the consistency of dough, it was taken out of the container and placed in a paper cup. Then samples were left to dry in the oven, without a mold (Figure 2d).

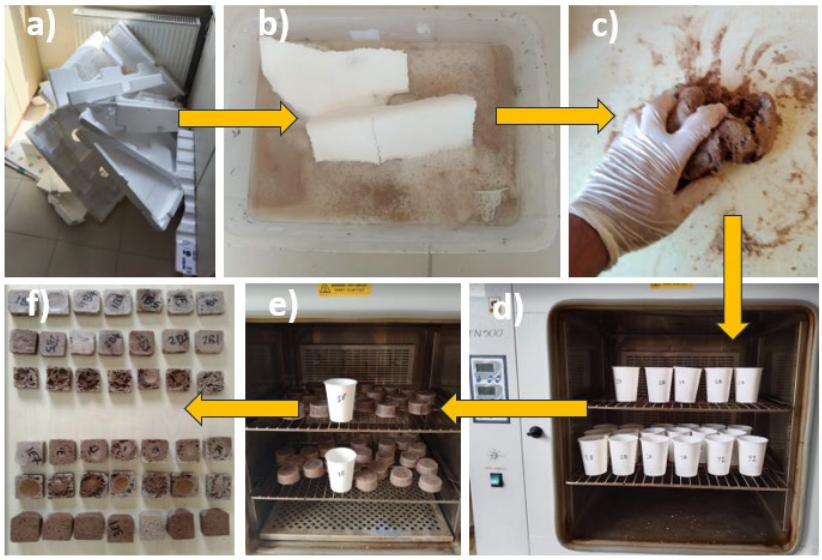

Figure 2. Sample preparing a) waste PS, b) melting by gasoline, c) blending with fillers (MF and GF), d) phase 1: oven at 100 °C, e) phase 2: temperature was raised to 190 °C, f) analysis samples.

Table 2. Material ratios.

Solvent (type)	Samples	Ingredient	PS (g)	MDF fine dust (g)	GF (g)	Solvent quantity (g)
GASOLINE	1B	Polystyrene + MF	200	100	–	100
	2B	Polystyrene + MF	200	200	–	100
	3B	Polystyrene + MF	200	300	–	100
	1E	Polystyrene + glass fiber	200	–	100	100
	2E	Polystyrene + glass fiber	200	–	200	100
	3E	Polystyrene + glass fiber	200	–	300	100

With the heat, the solvent in the composite was removed quickly. Normally, 100 °C was sufficient, but 190 °C was also used to understand whether high temperature affected the SR of the composite.

Samples were kept in the oven at two different temperatures for 30 minutes. The oven temperature was 100 °C in the first phase to remove the solvent in the PS composites and to increase the volume in the meantime. After the solvent gasoline in the PS matrix was completely removed, the samples were kept in the oven at 190 °C for 30 minutes in the second phase (Figure 2e). Thus, it was aimed to determine the effect of heat treatment on PS composite. Then, samples were removed from the oven and analysis samples were cut by 20 x 35 x 35 mm for thickness swelling (TS), water absorption (WA), density (DN), screw withdrawal strength (SR) analysis (Figure 2f). There is no specific standard for the method of removing the solvent from the composite after dissolving PS in solvents and adding filler. Different temperatures and waiting times were used in different studies (Adeniyi et al., 2022; Uddin et al., 2020). In our study, the solvent was removed from PS between the glassy transaction point (100˚C) and the melting temperature.

The prepared samples were characterized mechanically and physically. For mechanical characterization SR analyzes was performed according to the TS EN 320.

The prepared samples were conditioned in an air-conditioning cabinet under 65±5% relative humidity and 20±2 °C temperature conditions until they reached a constant mass. The samples were taken out from the air-conditioning cabinet and subjected to testing without waiting. The screw used for the experiments has a zinc body and a star tip as shown in Figure 3; The size of the screw is 4.5 mm x 38 mm and the screw pitch is 1.4 mm.

Figure 3. Screw which was used screw witdrawal strength (Uysal and Güntekin).

The screwing process was carried out according to the principles specified in the standards. In this direction, screws; (15±0.5) mm was placed in the holes drilled into the test pieces in such a way that all the teeth were embedded.

In SR experiments, the loading speed was 2 mm/min. The screw withdrawal strength (F) was calculated based on Equation 1.

$$F = \frac{Fmax}{d*lp} \qquad (1)$$

Here, Fmax: Maximum force of fracture (Newton), d: Screw diameter (mm), lp: Distance of the screw entering the board (mm).

For physical characterization, 2-hour thickness swelling (TS2h) and 24-hour thickness swelling (TS24h), 2-hour water absorption (WA2h), and 24-hour water absorption (WA24h), density (DN) analyses were performed according to TS EN 317, TS EN 322, TS EN 323 respectively.

The analysis results were evaluated using the statistical software program SPSS. One-way analysis of variance (ANOVA) was performed with a significance level of $P < 0.05$ to determine if there were statistically significant differences among the samples. To further analyze meaningful differences among the groups, Duncan's test was used. Duncan's test is a post-hoc test that is commonly used after ANOVA to determine which groups differ significantly from one another.

3. Results and Discussion

3.1 Physical Properties

When the densities of the samples (kept in the oven at 100 °C) are examined, it is seen that the composite densities increase as the amount of MF increases (Figure 4a). However, this is not the same for composites with GF added (Figure 4b). The composite density increased when the amount of GF was increased from 50 % to 100 % but decreased with the 150 % GF filler (Table 3). This can be explained by the fact that a greater volume increase occurs in the PS matrix with the addition of 150 % GF. While the samples were heated in the oven at 100 °C, the gas released may have been blocked by excess GF and this may have caused thickness swelling, that is, volume increase, in the matrix.

It was determined that the TS amounts of the samples were quite low (Figures 4a and 4b). When the MF was increased from 50 % to 100 %, the TS of the samples increased. However, it decreased when the amount of MF was increased from 100 % to 150 %. It is thought that this is caused by the increasing density as the MF ratio increases.

There was no significant difference in the TS when the GF was increased from 50 % to 100 % and 150 %. In the Duncan analysis, the TS was in the same group (Table 3). The amount of GF was increased from 50 % to % 100 and % 150, the TS increased. A similar situation also occurred in densities.

Table 3. Physical properties of samples.

Samples	Oven temperature: 100°					Oven temperature: 190°				
	TS (2h) (%) *P:0.138	**WA** (2h) (%) P:0.001	**TS** (24h) (%) P:0.001	**WA** (24h) (%) P:0.001	**Density** (kg/m^3) P:0.001	**TS** (2h) (%) *P:0.056	**WA** (2h) (%) P:0.001	**TS** (24h) (%) P:0.001	**WA** (24h) (%) P:0.001	**Density** (kg/m^3) P:0.001
1B	0.1 ab** (±0,07)***	2.6 a (±1.1)	1.8 cd (±1.6)	9.3 b (±3.7)	692 b (±75)	0.4 a (±0.25)	3.6 b (±1.5)	1.1 b (±0.40)	9.7 ab (±1.8)	532 b (±31)
2B	0.2 b (±0.12)	5.4 b (±0.87)	2.9 d (±0.7)	14.5 c (±1.6)	740 c (±19)	0.6 a (±0.27)	3.6 b (±1.09)	1.4 b (±0.74)	16.3 c (±1.9)	669 c (±13)
3B	0.1 ab (±0.3)	5.7 b (±2.1)	0.5 ab (±0.5)	9.6 b (±0.7)	838 d (±54)	0.5 a (±0.17)	3.6 b (±0.65)	0.4 a (±0.22)	8.9 a (±2.0)	835 e (±52)
1E	0.1 a (±0.3)	8.2 c (±1.6)	0.3 a (±0.4)	12.1 bc (±0.8)	775 c (±25)	0.5 a (±0.15)	1.9 a (±0.79)	1.1 b (±0.32)	12.3 b (±3.6)	773 d (±16)
2E	0.1 ab (±0.3)	1.5 a (±0.14)	1.3 ab (±0.5)	6.1 a (±0.3)	933 e (±34)	0.5 a (±0.31)	2.5 ab (±0.74)	1.0 b (±0.28)	7.4 a (±0.8)	902 f (±43)
3E	0.1 a (±0.6)	16.0 d (±3.4)	1.2 bc (±0.3)	31.0 d (±5.4)	521 a (±8)	0.6 a (±0.11)	7.3 c (±1.32)	0.9 b (±0.53)	41.0 d (±4.1)	489 a (±23)

*P: significant level, **Duncan group, ***Standard deviation

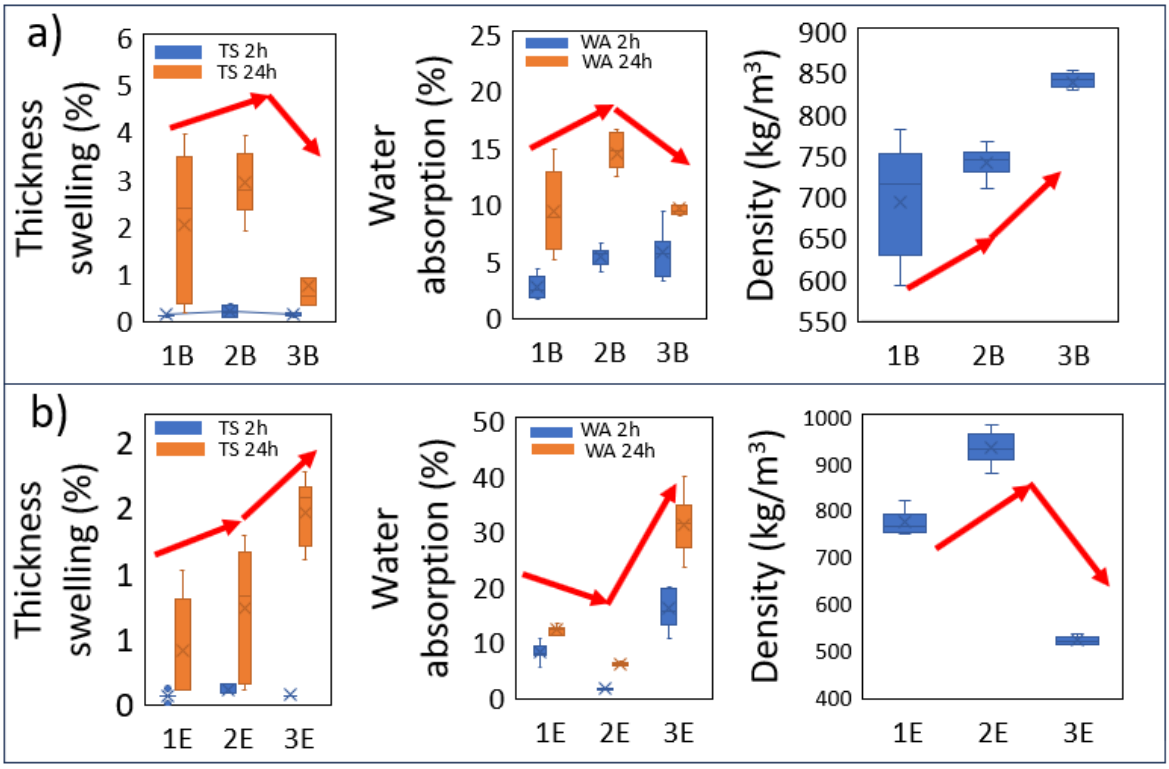

Figure 4. Physical properties of samples dried at 100°C, a) MDF fine dust added b) Glass fiber added.

The addition of 50 % GF filler increased the density, but the addition of 150 % decreased it. When the GF ratio increased to 150%, the composite foamed more. This caused the density to decrease. When WA was examined, the addition of GF and MF gave similar results. WA increased when filler amounts were increased from 50 % to 100 %. However, it

decreased when it was increased to 150 %. A direct relationship between WA and density has been determined. As the density decreased, WA increased and as the density increased, the amount of WA decreased (Figure 4a, 4b). With the addition of filler, macro voids were formed in the PS matrix. Macro voids caused low density. In addition, these voids caused more surface area on the inner surface of the matrix. With increasing surface area, PS composite absorbed more water.

Two different oven temperatures, 100 °C and 190 °C, were used in the study. A temperature of 100 °C was used to remove the solvent in the PS matrix. A temperature of 190 °C was used for the characterization of the composite after heat treatment. The physical properties of PS composites subjected to heat treatment at 190 °C for 30 minutes are given in Figure 5.

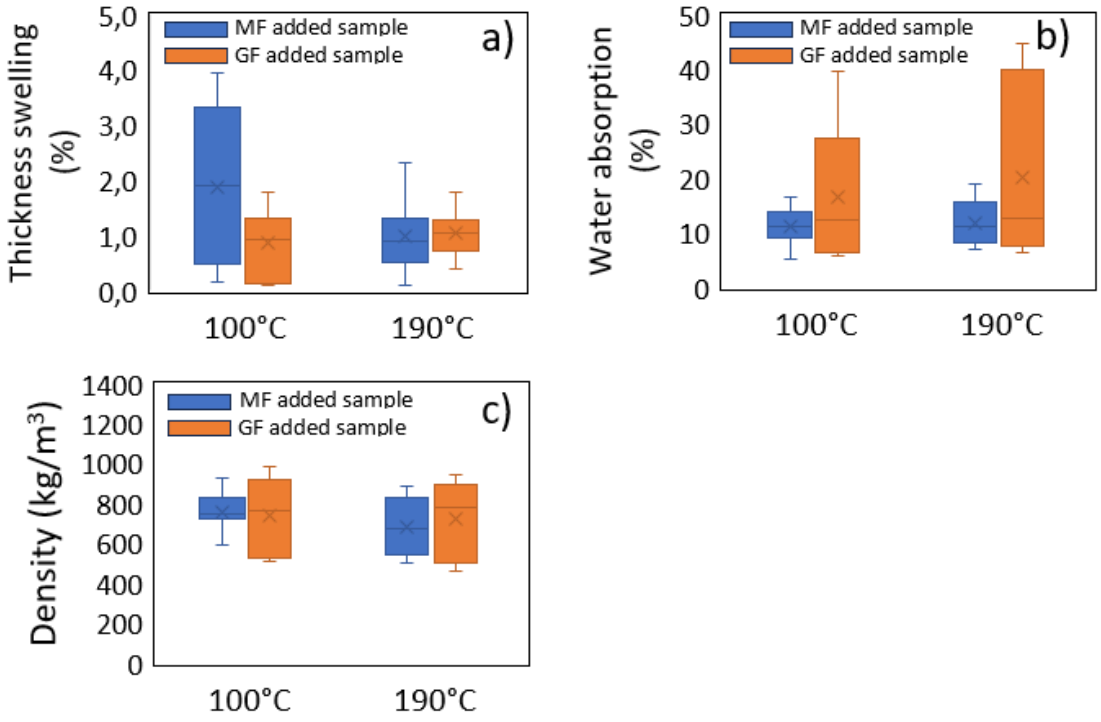

Figure 5. Physical properties of samples dried at 100°C and 190°C, a) TS b) WA, c) Density.

It was determined that there was a decrease in the TS (From 1,9 % to 1 % for MF and from 1 % to 0.9 % for GF) of the all PS composites treated from 100 °C to 190 °C. (Figure 5a). However, heat treatment (from 100 °C to 190 °C) increased (From11.1 % to 12% for MF and 16 % to 20% for GF) the WA of the samples (Figure 5b). Similarly, heat treatment also reduced the density (from 750 kg /m^3 to 658 kg/m^3 for MF and from 743 kg/m^3 to 721 kg/m^3) of the samples (Figure 5c). The decrease in density caused the WA of the samples to increase. Because the decrease in density caused more macro voids to form in the matrix. These gaps also caused more WA.

Chun et al. (2018) reported that the increase in the filling material (Husk fiber) caused more WA in PS composite. When the Husk filler was increased by 100 %, the WA of the composite increased by approximately 65 %. This result corroborates the findings of other researchers, including the study conducted by Penjumras et al. (2015). In our study, similar results were obtained. If it is desired to reduce the WA of PS composites, additional chemicals can be used. Additionally, different physical properties can be given to PS composites by using different chemicals. Chindaprasirt et al. (2015) added fire retardant diammonium phosphate (DAP) to the composite obtained from wood flour and PS mixture and reported that the WA and TS of the composite increased with the increase of DAP amount.

3.2 Mechanical Properties

The SR of the samples kept in the oven at 100 °C are given in Figure 6a, 6b, and heat treated at 190 °C are given in Figure 7a, 7b. In the wood industry, the screws and nail withdrawal resistance are very important. Especially in the selection of the material to be used in the core layer of WSP, it is desired that the SR be high. In this study, PS composites have SR that can be used in the core layer of WSP. When Figure 6a is examined, SR increased when the amount of MF was increased from 50 % to 100 %, but decreased when it was increased to 150 %. In a study, the tangential SR of Scots pine wood at 12 % moisture was determined at 201 kgf (31.4 N/mm^2) and 238 kgf (37.2 N/mm^2) of black pine (Ferah, 1995). In this study, SRs of the all samples were 10 - 82 N/mm^2 (Table 4).

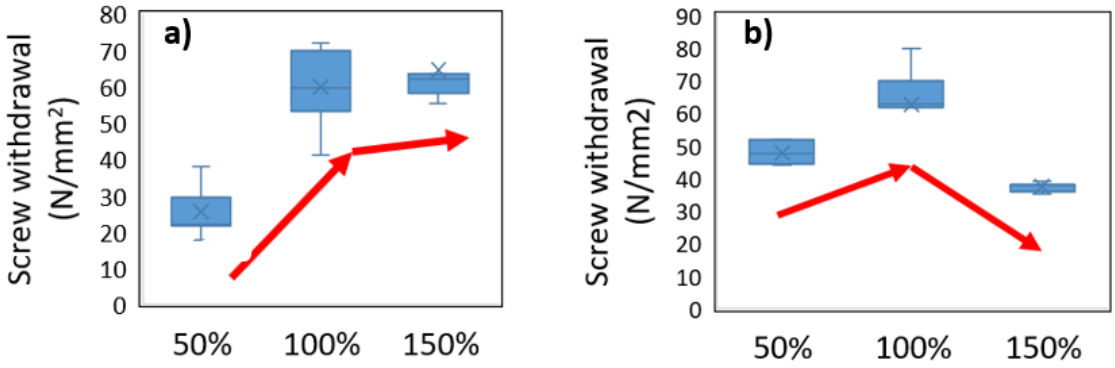

Figure 6. SR of samples dried at 100°C, a) MDF fine dust added b) Glass fiber added.

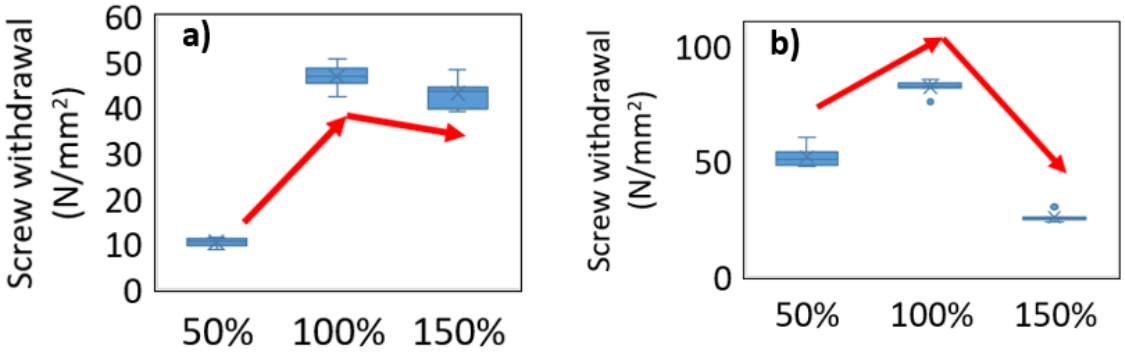

Figure 7. SR of samples dried at 190 °C, a) MDF fine dust added b) Glass fiber added.

When Table 4 is examined, it is seen that the SR of the samples heat treated at 190 °C are higher than 100 °C. Heat treatment (From 100 °C to 190 °C) increased the SR in both MF and GF-added samples. Increasing the filler amount to 150 % improved the SR in MF (Figure 6a) but decreased it with the addition of GF at 100 °C (Figure 6b).

Organic filler enhanced the mechanical strength of the PS composites. It is also stated by Sriprom et al. (2022) that lignocellulosic materials increase the binding in the PS matrix when treated with alkalis such as NaOH. Waste polystyrene (PS) was melted with acetone and added coconut husk fiber and banana stem fiber which were treated with NaOH and reported that the fillers (treated with NaOH) improved the mechanical strength of the composites (Sriprom et al., 2022).

Table 4. SR of samples

Samples	Oven temperature: 100°	Oven temperature: 190°
	SR (N/mm^2)	SR (N/mm^2)
1B	10	25
2B	47	60
3B	43	65
1E	52	48
2E	82	63
3E	26	37

Amount of organic fillers can increase the mechanical properties of the PS composite. Koay et al. (2018) reported that increasing the fiber content in the PS composite made from durian husk fiber and recycled PS foam resulted in higher tensile strength modulus but reduced elongation at break.

4. Conclusions

In this study, waste polystyrene was melted using gasoline, and waste MF and glass fiber were added as fillers. The study aimed to obtain a PS composite with high SR that can be used instead of wood material by recycling waste polystyrene (PS). MF is generally used as fuel in solid fuel boilers. With this study, MFs were added as filler (50-100-150 %) in melted PS. The samples were dried in the oven. Two different oven temperatures were used in the study. The samples were formed solid by removing the solvent at 100 °C. Also, samples were subjected to heat treatment at 190 °C to evaluate the heating affect. According to the results obtained, increasing the MF addition did not make a significant change in the TS, but increased WA. Similar results were obtained from the addition of GF. The addition of filler affected the density of the samples in different ways. While the densities increased continuously with the addition of MF, they decreased after 100 % with the addition of GF. SR increased further with the addition of GF. Heat treatment caused a decrease in the density of the samples but they increased WA. While heat treatment increased the SR of the samples in those with MF addition, it decreased in those with GF addition. MF is flammable, it is necessary to add mineral powder additive that prevents combustion. As a result, it was concluded that PS waste can be used in the core layer of WSP with the addition of MF and GF. However, the resulting cost and suitability for the place of use should be carefully calculated in terms of cost. To reduce the cost, different inexpensive solvents can be used to dissolve PS.

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