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Evaluation of recycled polyethylene-based composites filled with glass powder and aseptic carton particles

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Abstract

Plastic materials, glass beverage bottles, aseptic carton boxes, as well as paper and cardboard materials are among the most common household waste generated every day around the world. The recycling of such waste and the production of new products have been identified as part of the goal of responsible consumption and production in the sustainable development goals. In line with this goal, this study was conducted to produce a new composite material by mixing recycled plastic, glass and aseptic carton boxes in different proportions, and to determine some of the selected properties of the obtained composites. For example, composite plates were created with six different mixing ratios. Some technological properties of test samples were investigated. According to the data obtained, the addition of filler to the composite resulted in changes to its physical and mechanical properties. As the percentage of glass powder increased from 10 to 40 wt. %, the density increased, but the tensile strength decreased. In addition, the flexural and tensile modulus of all experimental groups increased as the filler was added compared to the control group. Moreover, as the weight percentage of glass powder increased, swelling and water uptake decreased.

1. Introduction

Currently, recycling of materials such as paper, cardboard, aseptic carton boxes, plastic, glass, copper, iron, steel and aluminium has become important. Many large-scale factories operate to recycle and reuse these materials or to utilise them in the production of various products. Paper and cardboard materials are first broken down in water in paper factories and, after a series of cleaning processes, are used in paper production. Waste glass, metals and plastic materials are first cleaned in factories and then melted and used in the production of new products.

In the world, four companies supply almost all the aseptic beverage cartons to the global food industry: Tetra Pak, SIG, Elopak and Greatview [1]. Tetra Pak produced 178 billion packages in 2024. Tetra Pak boxes and similar single-use materials made of glass and plastic present a significant waste problem. Studies are underway in various countries to recycle these types of waste, and composite materials are being produced from this waste.

Recycled glass materials have been utilised in various applications and for scientific research. For example, Sadik et al. [2] produced composites using recycled high-density polyethylene (HDPE) and glass powder and then investigated the mechanical properties of these composites. Bhaskar et al. [3] researched some of the mechanical properties of the glass powder-reinforced polymer composite. Heriyanto et al. [4] investigated the effect of particle size and a coupling agent on some selected properties of wood-plastic composites produced with recycled polypropylene (PP), sawdust and glass powder. Karunanayake [5] scrutinised the effects of glass powder on some selected properties of thermoplastics. Worku and Wubieneh [6] produced composite materials from waste polyethylene terephthalate (PET) bottles

reinforced with glass fibres and filled with recycled glass powder. In addition, Bal and Narlıoğlu [7] investigated the effect of particle size on some mechanical properties of HDPE-based composite filled with recycled glass powder.

Several important scientific studies are being undertaken on the recycling of aseptic carton boxes (ACBs), which are an inevitable household waste today. For example, Avella et al. [8] tested the selected properties of HDPE-based composite sheets filled with ACBs. Ayrilmis et al. [9] determined the selected properties of the ACB composites filled with rice-husk powder. Ebadi et al. [10,11] determined some of the technological properties of polyethylene-based composite sheets filled with ACBs. Mohareb et al. [12] and Hamouda et al. [13] investigated the mechanical properties and decay resistance of composites produced with ACBs. Aranda-García et al. [14] investigated various processing factors that affect composites filled with ACBs. In addition, Bal [15] produced composites using recycled PP, wood flour, and ACBs and investigated some of the properties of these composites.

As can be seen from these previous studies, new composites can be produced using waste polymers such as PP, PET and HDPE and waste filler materials, such as wood flour, glass powder and ACBs. In addition, previous studies have yielded scientifically successful results. However, there is no study on the production of a composite material using glass and carton beverage boxes as fillers. Therefore, the aim of this study is to produce a recycled polyethylene-based composite material filled with glass powder and ACBs and to evaluate the selected properties of the produced composites.

2. Materials and methods

2.1 Materials

In this study, three different materials were used for the production of composites: recycled low-density polyethylene (LDPE), denoted as R-PE, waste glass and waste ACBs. R-PE was used as a matrix in composite production, and glass powder (denoted as R-GP) and ground aseptic carton boxes (denoted as G-ACB) were used as filler material. R-PE was obtained from the Vepsan Plastik, Turkey (Fig. 1a). Waste glass bottles were collected from domestic use, smashed with a hammer and then ground at 25.000 rpm using a grinder (Demsan Brader 1500) for 2 minutes. The obtained glass powder was sieved using different mesh sieves (20, 40, 60 and 80). The glass powder that passed through an 80 mesh sieve (approximately 177 µm) was used in the production of composites (Fig. 1b). Waste aseptic carton boxes of the Tetra Pak brand were collected, shredded into small pieces and ground at 25.000 rpm with a grinder (Demsan Brader 1500) for 1 minute (Fig. 1c).

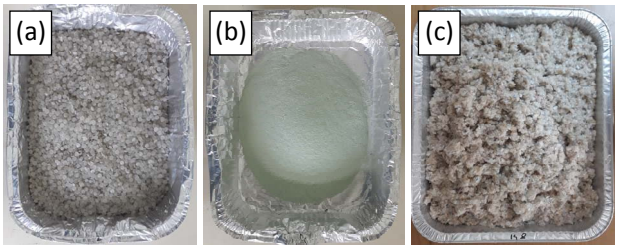

Figure 1. Materials: (a) recycled polyethylene, (b) sieved glass powder and (d) ground ACBs

The compositions of the composites are shown in Table 1. The R-GP and G-ACB were dried at 103 ± 2 °C. Then, the R-GP, G-ACB and R-PE were mixed before being processed in the extruder. The blend was compounded with a single screw extruder. The extruder barrel temperature was set to 160, 175 and 190 °C from the feeding section to the exit die section, respectively. The main screw speed was adjusted to 16 rpm. The extruded mixture was taken in filament form from the extruder exit that had a nozzle diameter of 3 mm. The filaments were cooled on a table in the air. The cooled blend was cut into pellets, and these pellets were ground using a grinder. The cooled filament was cut into pellets, and these pellets were remixed with the extruder. The extruded mixture in filament form was cooled on a table. The cooled filament was cut into pellets. The mixture was processed twice in the extruder to ensure that the composite was homogeneous.

Table 1. Composition of the composites

Group	1	2	3	4	5	6
R-PE, wt. %	100	60	60	60	60	60
R-GP, wt. %	0	0	10	20	30	40
G-ACB, wt. %	0	40	30	20	10	0

Then, the pellets were placed in a metal mould and transferred to a hot press at 190 ± 5 °C and 5 tons pressure. The blend was heated and melted for over 15 minutes. After the 15-minute pressing process, the metal mould was removed from the hot press and placed in a cold press for 5 minutes. A total pressure of 16 kg/cm^2 was applied for 5

minutes in the cold press. The board was taken from the metal mould, and a composite board was thus obtained with the dimensions of 3.5 × 175 × 175 mm (thickness × width × length).

2.2 Methods

Density, flexural, tensile and Shore D tests of the samples were determined according to ASTM D792, ASTM D790, ASTM D638 and ASTM D2240, respectively. The post-test images of the samples are given in Figure 2. Density values were measured by dividing the weight of test samples measuring 3.5 × 20 × 20 mm (thickness × width × length) in air by their volume in water. Flexural and tensile strength tests were performed using the universal testing machine (Natek, 10 kN). Flexural test samples were cut using a band saw machine with the dimensions of 3.5 × 20 × 80 mm (thickness × width × length). Sixteen test samples for each group were made to determine the flexural test values. The preload was set at 2 N, the support opening was 56 mm and the test speed was 2 mm/min. For the tensile test, sixteen test samples from each group were prepared with the dimensions of 3.5 × 20 × 165 mm (thickness × width × length). The preload was set to 5 N and the test speed was set to 2 mm/min. The elastic modulus values measured during the flexural and tensile tests are shown in the results tables. The Shore D test was performed by applying a 5 kg load on the Shore D durometer (Loyka LXD-D).

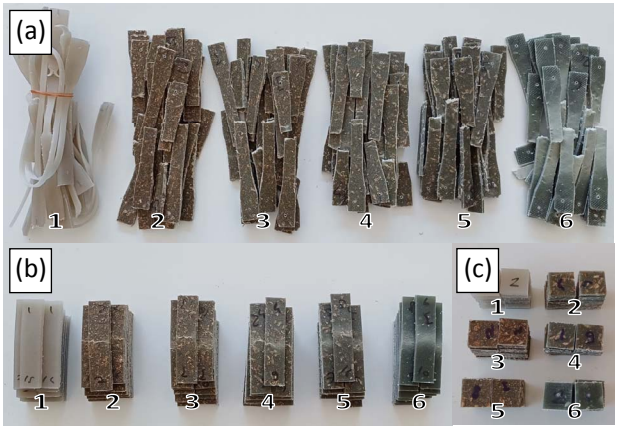

Figure 2. Test samples: (a) tensile test, (b) flexural test and (c) physical properties test

Test samples measuring 3.5 × 20 × 20 mm (thickness × width × length) were used to determine thickness swelling and water absorption according to ASTM D570. The test samples were immersed in water for 24 hours. At the end of the immersion time, they were removed from the water and the surface was cleaned with a dry cloth. The specimens were weighed and measured to calculate thickness swelling and water absorption. These tests were not performed on Group 6 because it was composed only of materials that do not absorb water, such as polyethylene and glass powder.

One-way ANOVA and Duncan tests were performed on the data obtained at the end of the tests using a statistical program (SPSS 13.0). Arithmetic means followed by the same letter are not significantly different from each other, using the Duncan multiple comparison test at $\alpha = 0.05$.

3. Results and discussion

The density test data are shown in Table 2. The density of the control group (Group 1) was 920 kg/m^3. The densities of the experimental groups (Groups 2 – 6) using G-ACB and R-GF fillers were significantly higher than those of the control group. Also, when comparing Group 2 with Group 6, the effect of R-GF on density was greater than the effect of G-ACB. The highest density was observed as 1166 kg/m^3 in Group 6. Similar results regarding density values were obtained in previous studies on polymer-based composite materials [4,7,15].

The data of the thickness swelling and water absorption tests of the composites are given in Table 3. The differences between the water absorption values are statistically significant. Parallel to the thickness swelling values, the water absorption values decreased as the percentage of G-ACB in the composite sheets decreased. The differences among the groups are statistically insignificant (NS). As the percentage of R-GP in the composite increased, the thickness swelling value decreased. One of the reasons for this is that G-ACB is a more hygroscopic material compared to R-GF. R-GF and polyethylene are not hygroscopic. This feature affects the water absorption values of composites. Low water thickness swelling and absorption values are positive features of composites used in outdoor applications and places in contact with water.

Table 2. Density test data, ANOVA p-value and Duncan test results

Group	1	2	3	4	5	6	p-value
X, kg/m^3	920	1038	1062	1105	1141	1166	< 0.001
SD, kg/m^3	4.2	10.1	9.6	15.0	13.9	13.4	
Duncan	A	B	C	D	E	F	

X – arithmetic mean; *SD* – standard deviation

Table 3. Thickness swelling and water absorption test data, ANOVA p-values and Duncan test results

Group	1	2	3	4	5	6	p-value
Thickness swelling							
X, %	–	1.19	1.13	1.10	1.03	–	NS
SD, %	–	0.29	0.35	0.23	0.48	–	
Duncan	–	A	A	A	A	–	
Water absorption							
X, %	–	2.31	1.42	1.10	1.03	–	< 0.001
SD, %	–	0.61	0.37	0.23	0.48	–	
Duncan	–	B	A	A	A	–	

X – arithmetic mean; *SD* – standard deviation; NS – statistically insignificant

Table 4 shows the flexural strength of the composite test samples. As the R-GP percentage increased, the deformation at bending increased, while the flexural strength and flexural modulus decreased. On the other hand, as the G-ACB percentage increased, the strength and stiffness increased. The highest flexural strength and flexural modulus values of 21.8 N/mm^2 and 773 N/mm^2, respectively, are in Group 2, where 40 wt. % G-ACB was used. The lowest flexural strength was 12.7 N/mm^2 in Group 6. The lowest flexural modulus was 351 N/mm^2 in the control group. The flexural strength of the test specimens in Groups 4, 5 and 6 was lower than that of the control group and Groups 2 and 3. Group 2 had the highest flexural strength. As the percentage of G-ACB decreased and the percentage of R-GP increased, the flexural modulus values decreased. Group 2 had the highest flexural modulus. Compared with the control group, the flexural modulus values of the other groups were higher. The difference among groups was significant.

As has been shown, the mechanical properties of many composites generally increase with density, although not all of them do. In previous studies on wood-plastic composites, as the percentage of filler in the composite materials increased, flexural strength increased in some studies [11,16,17], and decreased in others [4,6,15]. Conversely, as the percentage of filler in the composite material increased, the flexural modulus increased [9,11,15,17]. In addition, in most studies, as the percentage of filler in the composite material increased, deformation at bending value decreased [7,18,19].

Table 4. Flexural test data, ANOVA p-values and Duncan test results

Group	1	2	3	4	5	6	p-value
Flexural strength							
X, N/mm^2	17.4	21.8	20.2	16.6	14.3	12.7	< 0.001
SD, N/mm^2	0.5	1.8	1.3	1.0	1.0	1.1	
Duncan	C	E	D	C	B	A	
Flexural modulus							
X, N/mm^2	351	773	650	542	526	518	< 0.001
SD, N/mm^2	22	88	73	72	37	45	
Duncan	A	D	C	B	B	B	
Deformation at bending							
X, mm	19.5	14.3	16.2	16.7	18.6	19.0	< 0.001
SD, mm	0.4	2.8	2.2	2.0	0.7	0.6	
Duncan	C	A	B	B	C	C	

X – arithmetic mean; *SD* – standard deviation

The data from the tensile test are presented in Table 5, indicating that the highest tensile strength was measured in Group 1 (control group). The tensile strength of all other test sample groups was lower than that of the control group. Groups 4 and 5 had the lowest tensile strength values. As the percentage of G-ACB filler decreased in the experimental groups, the tensile strength decreased, except for Group 6. The differences in the tensile strength values between Groups 4, 5 and 6 were insignificant. Group 2 had the highest measured tensile modulus (301 N/mm^2) and the lowest value was in the control group (139 N/mm^2). The tensile modulus values of all experimental groups are higher than those of the control group. The difference is statistically significant (p-value < 0.001).

Many studies have been conducted to determine the effect of filler on the mechanical properties of composite materials produced with polyolefin group polymer matrices. Several of them showed that, in general, as the filler percentage increases, the tensile strength decreases, though the tensile modulus increases [4,6,7,9,15,17]. Fu et al. [20] noted that as the percentage of ACBs filler increased, the tensile strength increased. The authors of that study noted that factors such as particle size, particle/matrix interfacial strength and particle aspect ratio affect the strength of the composite. In other studies, the reason for the decrease in tensile strength was the incompatibility between the non-polar polymer and the polar filler material, resulting in an adhesion problem caused by this incompatibility [9,19].

Table 5. Tensile test data, ANOVA p-values and Duncan test results

Group	1	2	3	4	5	6	p-value
Tensile strength							
X, N/mm^2	10.0	7.5	6.9	6.2	6.2	6.5	< 0.001
SD, N/mm^2	0.7	0.7	0.5	0.7	0.6	0.4	
Duncan	D	C	B	A	A	A	
Tensile modulus							
X, N/mm^2	139	301	294	264	281	290	< 0.001
SD, N/mm^2	30	56	38	59	37	42	
Duncan	A	D	B C	B	B C	B C	
Elongation at break							
X, %	218	5.6	6.6	6.6	6.7	29	< 0.001
SD, %	93.6	0.9	1.1	1.2	1.0	11.1	
Duncan	B	A	A	A	A	A	

X – arithmetic mean; *SD* – standard deviation

The tensile strength of the fillers was generally lower than that of the polymer used. Thus, as the filler amount in the composites increased, the gaps between the filler materials increased, preventing stress distribution when tensile stress was applied, and causing increased brittleness [9,20-22]. The most significant difference in the tensile tests was in the elongation at break test results. Elongation at break was measured as 218 % in Group 1, while in the experimental groups it ranged from 5.6 to 29 %. Other researchers have reported similar results for the effects of filler materials on elongation at break [23-28]. Additionally, in a similar study, Kuzmin et al. [29] found that the elongation at break value decreased as the ACBs percentage increased in HDPE-based composite sheets produced with ACBs filler.

The hardness values of the composite materials are given in Table 6. The hardness of the experimental groups was higher than that of the control group. The hardness of Group 2 was higher than that of Group 6. The differences between the groups were significant. The highest hardness value was in Group 4, where G-ACB and R-GP were used in equal amounts. The R-GP is a more rigid material than the G-ACB. However, the volume of G-ACB added to the composite, although it had the same weight percentage, was much higher than the volume of R-GP. Therefore, the hardness values of the groups with a higher percentage of R-GP (Groups 5 and 6) were lower than those of the groups with a higher percentage of G-ACB (Groups 2 and 3).

Table 6. Hardness (Shore D) test data, ANOVA p-value and Duncan test results

Group	1	2	3	4	5	6	p-value
X	48	54	58	60	53	52	< 0.001
SD	1.2	1.6	1.2	2.4	0.7	0.7	
Duncan	A	C	D	E	C	B	

X – arithmetic mean; *SD* – standard deviation

Additionally, previous studies have reported that the hardness value of the composite material increases with an increase in the filler percentage. For example, Bal [15] determined that the hardness value of the composite material produced with polyethylene and wood flour increased with the increase of wood flour filler in the composite. In a later study, Bal and Narlıoğlu [7] determined that the hardness value of unfilled HDPE-based composite material did not increase statistically with the increase in the percentage of glass powder filler in the composite. However, Heriyanto et al. [4] showed that as the amount of wood flour in a composite decreased and the percentage of glass powder increased, the hardness value increased only insignificantly.

4. Conclusion

In this study, the researchers produced composite materials from household waste by mixing recycled plastic, glass powder and aseptic carton boxes particles in different proportions, and determined the selected properties of these composite materials.

According to the test results, the density of the composites increased with the increase in the percentage of glass powder filler. The effect of the glass powder on the density was higher than that of the aseptic carton boxes particles filler. The flexural strength increased as the aseptic carton boxes filler percentage increased. In addition, flexural modulus and tensile modulus of all composites (regardless of the filler type) increased compared to the unfilled polymer sample.

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