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Mechanical Analyses of Denim Fabrics Laminated with Recycled Polyethylene Packaging Wastes

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Abstract

Due to the increasing population and production rate in the world, the amount of waste accumulating in solid waste sites is increasing day by day. In particular, disposable packaging wastes go to landfills after they are used, and this situation poses a serious risk when evaluated in terms of solid waste management. On the other hand, the textile industry, which has a large production volume, causes tons of textile waste to be buried in solid waste sites. The major goal of this study is to produce 100% recycled laminated textiles by combining waste from denim fabric and polyethylene bottle caps, which are the priority waste categories for both industries. In this context, low and high density polyethylene waste bottle caps were recycled separately by the hot press method, and the matrix plates obtained were laminated to waste denim fabrics. The physical and mechanical properties of the produced laminated fabrics were tested, and the results were discussed by comparing them with the test results of polyethylene plates and denim fabrics. The findings demonstrated that high density polyethylene could be processed more easily in the lamination process and also imparted better mechanical properties to the fabric to which it was laminated compared to low density polyethylene. These laminated textiles with 100% waste content are expected to provide a sustainable substitute for value-added products that can be used especially in outdoor application areas such as awnings with their improved properties.

Keywords: Polyethylene, Packaging waste, Denim fabric, Laminated fabric, Recycling

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Geri Dönüştürülmüş Polietilen Ambalaj Atıkları ile Lamine Edilmiş Denim Kumaşların Mekanik Analizi

Öz

Dünyada artan nüfus ve üretim hızı nedeniyle katı atık sahalarında biriken atık miktarı her geçen gün artmaktadır. Özellikle tek kullanımlık ambalaj atıkları kullanıldıktan sonra düzenli depolama sahalarına gitmekte ve bu durum katı atık yönetimi açısından değerlendirildiğinde ciddi bir risk oluşturmaktadır. Öte yandan, büyük bir üretim hacmine sahip olan tekstil sektörü, tonlarca tekstil atığının katı atık sahalarına gömülmesine neden olmaktadır. Bu çalışmanın temel amacı, her iki sektör için de öncelikli atık kategorileri arasında yer alan denim kumaş ve polietilen şişe kapaklarının atıklarını birleştirerek %100 geri dönüştürülmüş lamine tekstil ürünleri üretmektir. Bu kapsamda düşük ve yüksek yoğunluklu polietilen atık şişe kapakları sıcak pres yöntemiyle ayrı ayrı geri dönüştürülmüş ve elde edilen matris plakalar atık denim kumaşlara lamine edilmiştir. Üretilen lamine kumaşların fiziksel ve mekanik özellikleri test edilmiş ve sonuçlar polietilen plakalar ve denim kumaşların test sonuçları ile karşılaştırılmıştır. Bulgular, yüksek yoğunluklu polietilenin laminasyon işleminde daha kolay işlenebileceğini ve ayrıca lamine edildiği kumaşa düşük yoğunluklu polietilene kıyasla daha iyi mekanik özellikler kazandırdığını göstermiştir. %100 atık içeriğine sahip bu lamine tekstillerin, geliştirilmiş özellikleri ile özellikle tente gibi dış mekan uygulama alanlarında kullanılabilecek katma değerli ürünlere sürdürülebilir bir ikame sağlaması beklenmektedir.

Anahtar Kelimeler: Polietilen, Ambalaj atıkları, Denim kumaş, Lamine kumaş, Geri dönüşüm

1. INTRODUCTION

Municipal solid waste (MSW) disposal is a huge problem for developing countries. About 11% by the weight of MSW consists of waste plastics such as polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and polystyrene (PS) [1]. The main reason for this is that almost 91% of all plastic produced in the world is not recycled. It is thought that the cumulative amount of plastic waste in 2050 will reach 12,000 mt if plastic production continues at the same pace and if no change is made in the waste management trend. On the other hand, when these data are evaluated in terms of greenhouse gases, it is predicted that carbon dioxide emissions will increase approximately 4 times in 2050 compared to 2015. Therefore, every virgin plastic that enters production will continue to threaten the environment due to both solid waste and greenhouse gas emissions [2].

Polyolefins play a leading role in the packaging industry thanks to their good mechanical properties, easy processing and low cost. According to 2018 data, Europe has 49% plastic demand for polyproylene (PP) and polyethylene (PE), and the largest shareholder of this plastics industry is the packaging industry with 39.9% [3]. Polyethylene has the largest share in international trade, and the global demand for it is increasing day by day [4].

Polyethylenes are classified according to their density, which is a result of their degree of crystallinity, and the type and content of branches. The chemical formulas of these polyethylenes, the most common commercial examples of which are high density polyethylene (HDPE) and low density polyethylene (LDPE), are the same, but the density of their molecular chains is different. HDPE has a high molecular weight resulting in a high degree of crystallinity and consists of a linear structure with little or no branching. LDPE, on the other hand, has lower crystallinity compared to HDPE because it consists of a chaotic structure with short and long chain branches [5]. These two polyethylenes are polymers that can be reprocessed under heat with different properties they exhibit.

It is important to recycle or reuse plastics after use in order to reduce environmental pollution caused by plastic packaging waste. In this sense, there are remarkable developments under the name of sustainability today. For example, while the rate of recycled plastic was 16% worldwide in 2016, this rate was given as 32% for Europe in 2018. Although the result that recycling has increased by 2 times is promising, it is obvious that the recycling percentage is still insufficient [6].

Like the plastics industry, the textile sector is one of the leading industries that generate a large amount of waste. In direct proportion to the increase in population and income level, textile consumption increases at a high rate and this leads to unwanted waste textile production worldwide [7]. More than millions of tons of textile waste is generated worldwide every year, but only less than 20% of this is recycled [8].

In textile industry, the impact of denim production on environmental degradation is extremely dangerous due to both being one of the most widely used fabrics and the high amount of chemicals used during its production [9, 10]. Cotton is the main raw material used in denim production [11]. The reuse of cotton will reduce cotton production, which results in a very high use of water, fertilizers and pesticides [12]. Waste cotton fabrics and fibers are recycled and reused in many different areas. The abundance of raw materials, low density, high biodegradability and low price provide advantages in the use of waste cotton fibers as reinforcement material in composite structures [7].

In the literature, it is possible to find some studies that focus on the production of fabric-reinforced polyolefin-based composites. For instance, in a study of Sayem et al. commercial HDPE, PP and Nylon 6 sheets were reinforced with jute fabrics using compression moulding techniques [13] whereas Lv et al. manufactured decorative wood fiber and HDPE composites with canvas or polyester fabrics by hot and cold pressing techniques [14]. In almost a similar way, Mayer et. al produced Kevlar fabric reinforced HDPE and PP film-based laminates by hot press method for ballistic applications [15]. On the other hand, the number of studies on environmentally friendly production using recycled polyolefins in laminated fabrics is quite limited. Rokbi et al. have a study on investigation of tensile properties of plain woven jute fabric reinforced recycled polypropylene film composites [16]. Unlike all the mentioned studies, in this study, HDPE and LDPE plates produced from recycled polyethylene bottle caps are laminated to waste denim fabrics by hot press method and the physical and mechanical properties of these laminated fabrics are evaluated by comparing them with the results of pure recycled PE plates and denim fabrics. Rather than using pure polymers in this study, plates were made of recycled post-consumer waste polymers, and denim fabric waste, the textile industry's most chemically-intensive fabric type, was recycled instead of being disposed of in landfills. Leading the subsequent studies on sustainability will be recycling the wastes of these two significant industries (textiles and plastics), which produce enormous volumes of garbage.

2. MATERIALS AND METHODS

2.1. Materials

In this study, 240 g/m^2 post-production wastes of denim fabrics (98% cotton, 2% elastane) with twill weave structure supplied from Calik Denim and used as a reinforcement material whereas post-consumer wastes of HDPE and LDPE water bottle caps that are collected from ITU Gumussuyu Campus and recycled, are used as matrix materials.

2.2. Methods

2.2.1. Preparation of Matrix Plate

Before the production of the laminated fabrics within the scope of the study, the matrix material is prepared in the form of a plate. For this purpose, LDPE (24 pieces, Figure 1a) and HDPE (117 pieces, Figure 1b) bottle caps arranged between two pieces of Teflon paper are placed in the hot press machine. Considering the melting temperatures of the polymers, the temperature is adjusted to 160°C for HDPE plate production and to 140°C for LDPE plate production. The materials are kept at these temperatures and 20 tons of pressure for 1 hour, then the temperature is turned off and the material is left to cool for about 3-4 hours under the same pressure. The matrix plate obtained can be seen in Figure 1c.

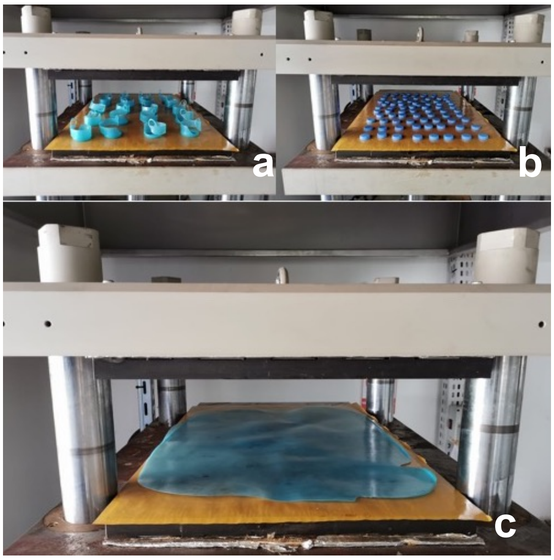

Figure 1. a. LDPE and b. HDPE bottle caps c. matrix plate

2.2.2. Preparation of Laminated Fabrics

The purpose of lamination on denim fabric is to improve the mechanical properties of the fabric, as well as to make it a suitable material for various outdoor applications by imparting water resistance.

In order to obtain laminated fabric, LDPE and HDPE matrix plates produced in 50*80 cm dimensions are placed in the hot press together with one layer of denim fabric cut in the same dimensions. Similarly, Teflon paper is used to prevent the matrix plate from sticking to the metal sheets of the hot press. HDPE and LDPE laminated fabrics are kept for 1 hour under 20 tons of pressure at temperatures of 160 °C and 140 °C, respectively. After 1 hour, the temperature is turned off and the samples are kept under the same pressure for 18 hours to prevent curling. Laminated fabric structures can be seen in Figure 2.

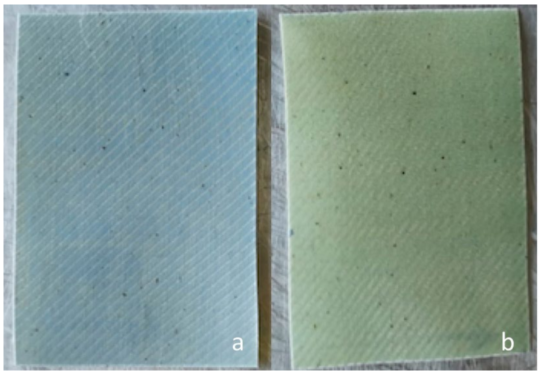

Figure 2. Laminated fabrics a. HDPE b. LDPE

2.2.3. Physical Analysis

The thickness of the waste denim fabric, recycled HDPE and LDPE plates and the laminated structures are measured by a digital micrometer (Standard Gage) while the areal density and fiber weight ratio values are calculated based on measured experimental weight data.

2.2.4. Mechanical Analysis

The tensile strength of the laminated fabric structures, denim fabrics and plastic plates are measured in accordance with the TS EN ISO 13934-1 standard by using the Titan[2] universal testing machine. Since woven fabrics have different performance properties in weft and warp directions, denim fabric and laminated fabrics are tested separately in weft and warp directions. Five different measurements are done for each sample group and the mean values are given together with the standard deviation (SD) values. The maximum load values obtained as a result of the test are divided by the cross-sectional area (width x thickness) of the test samples and the tensile strength values of the materials are calculated. Double tear strength is realized with same test machine according to TS EN ISO 13937-4 standard (Figure 3). Maximum tear force data is divided into thickness of the sample to calculate tear strength values and results are given in mean and standard deviation values of five samples.

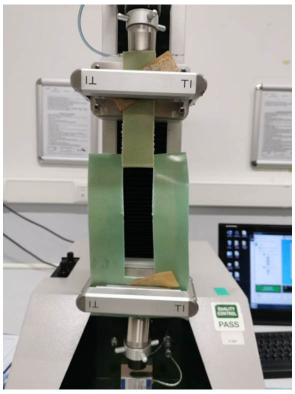

Figure 3. Double tear strength test

The drop-weight impact tests of the laminated fabrics are performed by BESMAK impact testing machine according to the ASTM D7136 standard. Five samples from each test group are exposed to 12 Joule impact energy. The results are supported by visual damage models as well as numerical data on absorbed energy, maximum load and displacement. Numerical results are given with mean and standard deviation values.

3. RESULTS AND DISCUSSION

3.1. Physical Analysis

The thickness, areal density and fiber weight ratio values of the waste denim fabric, recycled HDPE & LDPE plates and the laminated structures are given in Table 1. It is seen that the thicknesses of the laminated structures are lower than the sum of the thicknesses of the fabric and plastic plates. This shows that the lamination process is achieved properly and both HDPE and LDPE plates adhere well to the fabric surface by penetrating the yarns that make up the fabric.

Compared to HDPE plates, LDPE plates have a more viscous structure under heat, which makes it somewhat difficult for LDPE plates to penetrate the fabric in a molten phase. Therefore, due to the thicker LDPE layer in the laminated structure, a lower fiber weight ratio is achieved in LDPE laminated composite structures compared to HDPE laminated composites. The areal densities of the samples also support this result.

Table 1. Physical properties of samples

Sample Codes	Thickness [±SD] (mm)	Areal Density [±SD] (g/m^2)	Fiber weight ratio [±SD] (%)
Denim	0.38[±0.02]	240[±0.02]	
HDPE	0.34[±0.03]	307[±0.02]	-
LDPE	0.52[±0.03]	419[±0.02]	-
Denim-HDPE	0.49[±0.06]	510[±0.02]	47 [±0.02]
Denim-LDPE	0.63[±0.04]	575 [±0.02]	42 [±0.02]

3.2. Mechanical Analysis

3.2.1. Tensile and Tear Strength Analyses

Tensile and tear strength values of fabrics (Denim-warp & Denim-weft), recycled matrix plates (HDPE & LDPE) and laminated fabrics (Denim-HDPE-warp, Denim-HDPE-weft, Denim-LDPE-warp & Denim-LDPE-weft) are given in Table 2. When the tensile strength results of fabric samples are examined, it is seen that the tensile strength value obtained in the warp direction is approximately 65% higher than the value obtained from the weft direction. Considering the characteristic features of woven fabrics and weave type (twill), this is an expected result. Warp yarns per inch is one the most dominant factor determining the strength of fabric in warp direction [17].

Table 2. Tensile and tear strength values of samples

Sample Codes	Tensile strength [±SD] (N/mm^2)	Tear strength [±SD] (N/mm)
Denim-warp	53.72 [±2.70]	159.03 [±16.02]
Denim-weft	32.05 [±0.63]	128.79 [±9.11]
HDPE	27.02 [±1.01]	28.10 [±5.34]
LDPE	16.32 [±0.92]	10.64 [±1.09]
Denim-HDPE-warp	71.92 [±0.31]	61.12 [±5.99]
Denim-HDPE-weft	39.81 [±0.44]	59.23 [±5.12]
Denim-LDPE-weft	46.15 [±1.23]	41,92 [±4.87]
Denim-LDPE-weft	29.32 [±1.09]	29.25 [±3.64]

When the tensile strength values of the plates are examined, it is noticed that HDPE plate has a higher tensile strength than LDPE. This can be resultant from the density differences of these polyethylenes. Density, which is defined as the measure of short chain branches, is one of the most important parameters that determine the properties of polyethylene. The decrease in density causes a decrease in the crystallinity ratio, which causes the final material to be softer and more flexible, with an increase in toughness and a decrease in yield strength [5].

In the samples laminated with HDPE and LDPE, a higher tensile strength value is obtained in the warp direction, just like in the fabric since the mechanical properties of coated fabrics depend on the those of the fibers that it contains and weave type [18]. With the lamination of the fabric with HDPE plate, an increase of 36% and 25% is observed in the tensile strength values in the warp and weft directions, respectively. However, 8-13% decrease in tensile strength is observed in LDPE laminated fabrics. It is thought that the lower tensile strength value of LDPE plate (16.32 MPa) in comparison to denim fabrics (32.05-53.72 MPa) causes this result.

However, it is very difficult to ensure homogeneous dispersion of natural raw material reinforcement materials in the thermoplastic matrix. This is because the reinforcement material is hydrophilic while the matrix material is hydrophobic, which makes it difficult to obtain a durable interface and reduces stress transfer from one component to another. For this reason, the positive effect to be obtained may increase even more if various surface modifications are carried out [19].

Considering the tear strength test results, it is seen that the tear strength of laminated fabrics is lower than that of pure fabrics. This can be explained by the fact that the melted polyethylene not only disperses between the yarns, but also diffuses between the fibers, causing the structure to become waxy, and therefore the structure cannot resist at the time of tearing. The mobility of the fibers and yarns that make up the fabric is important for obtaining high tear strength. When a coating is applied to the fabric, it restricts the fibers and the existing mobility of the yarns, resulting in a decrease in the tear strength of the fabrics regardless of the coating type [20]. On the other hand, it is obvious that HDPE and HDPE laminated fabrics show better tear strength than LDPE and LDPE laminated fabrics.

3.2.2. Drop-weight Impact Analysis

Drop-weight impact resistance test results are given in Table 3 and Figure 4.

When the absorbed energy values of LDPE and HDPE based laminated structures are compared, it has been determined that the energy absorbed by HDPE laminated structures is higher. This result can be supported by the higher tensile strength value of HDPE plates in comparison to LDPE plates (Table 2). Moreover, the fact that HDPE laminated composites have a higher fiber weight ratio than LDPE laminates is considered as one of the reasons for this situation. In addition, in parallel with the increase in the fiber weight ratio, it is seen that the maximum force that the material can bear increases.

Table 3. Drop-weight impact resistance test results

	Max load [kN]	Absorbed Energy [J]	Absorption ratio [%]	Displacement [mm]
Denim	-	-	-	-
HDPE	0.33 [±0.06]	0.57 [±0.16]	4.75	7.19 [±0.29]
LDPE	0.36 [±0.03]	0.45 [±0.03]	3.75	5.85 [±0.26]
Denim-HDPE	0.39 [±0.08]	0.60 [±0.19]	5.00	5.61 [±0.33]
Denim-LDPE	0.43 [±0.15]	0.51 [±0.58]	4.25	3.89 [±2.06]

According to the visual damage patterns represented in Figure 4, although full penetration is observed for all samples, it is clearly noticed that the damage characteristics of HDPE and LDPE plates thus their laminates are exactly different from each other.

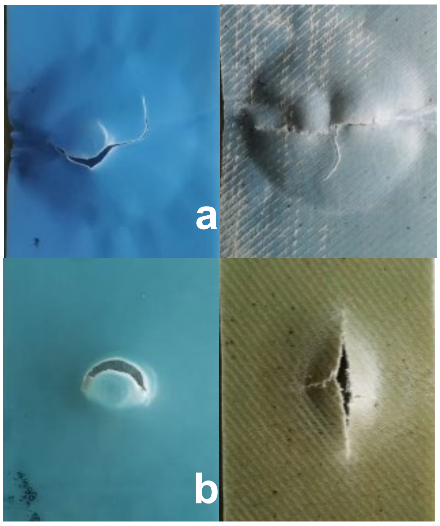

Figure 4. Damage patterns of the samples. a. HDPE plate and the Denim-HDPE sample b. LDPE plate and the Denim-LDPE sample

HDPE and HDPE laminates, which have higher absorbed energy values, are more resistant to the load acting at the time of damage and meet this load with a wider area, while it has been observed that a very smooth damage zone is formed only in the geometry and dimensions of the striking tip especially in pure LDPE samples with lower absorbed energy values. It is also seen that the characteristic features of this damage geometry have changed with the woven fabric structure added to the LDPE plates and it has been damaged more in the form of tearing.

4. CONCLUSION

In this study, waste polyethylene bottle caps are converted into matrix material and laminated to waste denim fabrics. The physical and mechanical properties of laminated fabrics produced using both HDPE and LDPE polymers are compared with pure HDPE and LDPE plates and denim fabric. The prominent results show that HDPE has easier processability than LDPE, so it can spread more easily into the textile structure. This situation directly manifests itself in the produced plate thicknesses and fiber weight ratios. It is also known that HDPE polymer has more advantageous mechanical properties than LDPE due to its chemical structure. This results in higher tensile strength and enhanced impact resistance values in HDPE laminated fabrics compared to LDPE laminated fabrics. On the other hand, regardless of the type of polyethylene, the lamination process reduces the tear strength of all fabrics since it restricts the movement ability of the yarns that make up the fabric. These produced laminated fabrics have the feature of being 100% recyclable, exhibit better strength properties than pure plastic plate and denim fabric, and become suitable for outdoor use with the waterproofing they offer. On the other hand, depending on the application area, the direction of tension that the fabric will be exposed to should be taken into account, and accordingly the weft and warp directions should be determined. This product group can be used as the main material or component in urban furniture in park and garden applications, as well as in personal products such as shopping bags.

This study, which develops an innovative material to obtain value-added products by using completely waste materials, also contributes to solid waste management and supports the understanding of sustainability.

5. ACKNOWLEDGMENT

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