TEKSTİL VE KONFEKSİYON

VOL: 33, NO. 1
DOI: 10.32710/tekstilvekonfeksiyon.1099223

The Effect of Various Textile Wastes (Human Hair, Denim and Pantyhose) on the Mechanical Properties of Composite Materials

Hande Sezgin 0000-0002-2671-2175

Istanbul Technical University, Faculty of Textile Technologies and Design, Textile Engineering Department, Istanbul, Türkiye

Corresponding Author: Hande SEZGİN, sezginh@itu.edu.tr

ABSTRACT

As technology advances and people's needs rise, the amount of waste produced rises in tandem with increased productivity in every industry. Aside from the fact that clothing is one of the most basic human necessities, the unstoppable growth of the fast fashion trend in recent years has boosted both the textile industry's production and waste. The goal of this research is to recycle these textile industry wastes and use them in a different sector. In this context, the mechanical properties (Charpy impact strength, drop-weight impact strength, tensile strength, and flexural strength) of hybrid composite structures composed of recycled textile wastes (denim waste, human hair waste, and pantyhose waste) and E-glass plain woven fabric are compared to those of E-glass plain woven fabric reinforced composite structures. While the vacuum assisted resin transfer method is used for production, epoxy resin is employed as the matrix material. The mechanical results reveal that, aside from tensile strength, the mechanical properties of the testile waste (denim, human hair, and pantyhose) and E-glass fabric reinforced hybrid composite constructions can compete with those of the pure E-glass fabric reinforced sample. In both impact strength tests, the hybrid samples reinforced with human hair outperform the other samples, whereas the denim waste hybridized samples get the highest flexural strength values. Besides that, the statistical significance of all results is evidenced by a 2-sample t-test.

ARTICLE HISTORY
Received: 06.04.2022
Accepted: 23.11.2022

KEYWORDS

Denim waste, E-glass fabric, human hair, pantyhose waste, recycling

1. INTRODUCTION

The need of recycling waste materials is becoming more widely recognized in light of climate change and gradual depletion of natural resources [1]. The textile industry is the world's second most polluting industry, accounting for 10% of total global carbon emissions [2]. The spread of the concept of fast fashion caused a large number of textile materials to go to landfills [3, 4]. While the amount of textile waste produced is increasing on a daily basis, a study found that in 2030, an individual will generate approximately 17.5 kg of textile waste per year [3]. This demonstrates how crucial the recycling of textile materials with varied life cycles (short-life textiles - disposable textiles, etc., medium-life textiles - garments, carpets, etc., long-lasting textiles - construction textiles, etc.) is as an environmental concern. The textile wastes are divided into three main categories as; production waste, preconsumer waste, and postconsumer waste. Production waste includes waste from various textile manufacturing procedures, while preconsumer waste covers unsold/damaged products in retailers, and postconsumer waste comprises products that the owners no longer desire to use. These waste groups can be recycled using mechanical, chemical, or thermal processes. The most popular process is mechanical recycling, which is based on a technique that converts textile materials to smaller pieces such as yarns or fibers [1].

Textile materials are manufactured from both synthetic and natural materials. Non-renewable petroleum-based polymers are the raw material source for synthetic-based

To cite this article: Sezgin H. 2023. The Effect of Various Textile Wastes (Human Hair, Denim and Pantyhose) on the Mechanical Properties of Composite Materials. *Tekstil ve Konfeksiyon* 33(1), 95-103.

fibers, which account for the vast bulk of textile fibers. Fibers made from these polymers by industrial chemical synthesis procedures withstand environmental degradation and require many years to disappear in nature due to their hydrophobic and extremely crystalline characteristics [5, 6]. Natural fibers, which appear more innocent than synthetics and are supposed to be harmless to nature, require a huge amount of fertilizers and pesticides that can harm the environment and human health, as well as a large amount of energy and water to manufacture [5, 7]. Given the environmental damage caused by both natural and synthetic fibers, the need of recycling these materials is obvious. Textile materials are recycled for reuse in the textile industry as well as in other sectors. Recycled textile materials can be utilized to produce garments, filler materials, insulation materials, and as reinforcement materials in composite structures [8-10]. Waste textile materials can be used in a variety of ways in composite materials. Fabric, yarn, fiber, and nano/micro particle fillers are examples of these forms [3]. Textile materials are preferred as reinforcement materials in composite structures because they offer excellent strength, stiffness, and fatigue resistance [11].

The primary goal of producing textile-based composite materials is to achieve good performance qualities while reducing material weight and cost [12]. Glass fiber, which has one of the best combinations of these three qualities, accounts for more than 87% of the reinforcement material in textile-reinforced composite constructions [13]. There are various types of glass fibers, and E-glass fibers are most commonly employed in composite structures due to their moderate modulus, low cost, and high strength values [14]. E-glass fiber-reinforced composites are commonly used in automobiles, boats, pipes, water tanks, and aircraft [15]. Despite its great performance, glass fiber is now being substituted with natural and/or recycled materials due to a decline in raw material resources and an increase in sustainability awareness [13].

Three distinct textile wastes (denim, pantyhose, and human hair) are applied as reinforcement material in composite structures in the scope of this investigation. The first waste category is discarded denim fabrics. Denim manufacture is one of the most environmentally destructive textile processes. For denim finishing operations such as sandblasting and aging, several toxic chemicals are employed, and these chemicals are intermingled with water resources [16]. Furthermore, considering the environmental damage caused by the manufacture of cotton fiber utilized in denim production, the relevance of recycling this waste group is widely understood. Cotton is the most common natural fiber in the textile industry, with denim being the most popular application [17-19]. The textile sector is growing at a rapid pace, and demand is rising. Many cotton-producing countries, however, have had to restrict their cotton planting areas due to dwindling water resources [17]. While cotton cultivation is estimated to use 1-6% of the world's total fresh water, producing 1 kg of cotton lint requires 10000-17000 L of water [20]. In many countries, recycling cotton waste is one of the key options to address this issue and ensure cotton self-sufficiency [17]. Cotton fiber's elastic recovery property, high strength, elongation at break in the dry condition, and resistance to thermal deterioration all contribute to its use as a reinforcement material in composites. These composites are commonly utilized in the interior panels of automobiles [21].

Waste pantyhose is the second type of waste. It is a waste product of the textile industry, having a short lifespan and a thin and flexible construction that renders it unsuitable for reuse. As pantyhose slip away after a few wears, consumption and waste are fairly considerable. According to a 2016 UK survey, a woman spent £3,000 on pantyhose throughout her lifetime [22]. Because they contain coal and petroleum-based raw materials, these polyamide-based textile products, which may contain elastane at particular ratios, disintegrate in nature for a long period [22]. Due to its elastic modulus, abrasion resistance, hardness, tensile strength, low friction coefficient, impact absorption capacity, thermal stability, and low density, polyamide fibers are favoured as a reinforcing material in composite materials, notably for use in armors [23-26]. Polyamide fibers with hydrophilic features offer high toughness and very good elastic properties due to the crystalline region composition of 65-85% [2].

Human hair is the final waste group examined in this study. It is not used in the manufacture of textiles but it is an animal fiber. It is regarded as a useless material nearly everywhere in the world and is disposed of in municipal landfills [27]. Many harmful gases, such as ammonia, sulfur dioxide, and hydrogen sulphides, are generated when attempting to eliminate this waste group by burning [28]. Although plant fibers are the most commonly utilized reinforcement material in composite structures, animal fibers, including human hair, are also used [29]. Superior tensile strength, moderate degradation rate, hydrophilic qualities, low cost, unique chemical composition, and elastic recovery properties are some of the properties of human hair fiber that make it a promising reinforcement material [13, 29-31].

Looking through the literature, it is obvious that there are studies that investigate the use of denim wastes [32-41] in polymer composite constructions. There are, however, only a few investigations on polymer composites reinforced with human hair [42-47], and none on waste pantyhose-reinforced composite structures. In one of these studies, Zonatti et al. (2015) produced various composites using different thermoset resins (epoxy, polyester orthophthalic, and polyurethane) and recycled denim wastes. The fiber ratios of the composites were kept constant at 30%. The obtained results showed that the tenacity and Young's modulus values of denim waste-reinforced epoxy-based composites increased by two times when compared to pure epoxy resin, whereas the tenacity and Young's modulus values of denim waste-reinforced orthophthalic polyester resin-based composites increased by two and three times, respectively, when compared to pure orthophthalic polyester resin. There were no substantial changes in these parameters in polyurethane resin composites [40]. In the study conducted by Baccouch et al. (2022), cotton, polyester, and cotton/polyester wastes were brought into nonwoven surface form and composite panels were produced by vacuum infusion technique. The mechanical, thermal, and acoustic properties of nonwovens and composite samples were investigated in this study, which utilized cotton wastes obtained from discarded denim fabrics. The results showed that nonwoven samples produced with 100% denim waste had the highest specific Young’s modulus, specific tensile strength, and elongation values, whereas 100% denim waste reinforced composite structures had the highest specific Young’s modulus, specific tensile strength, and impact strength values [41]. Senthilnathan et al. (2014) constructed hybrid composite structures employing several reinforcement materials (coconut fiber, human hair fiber, and glass fiber) in an epoxy resin matrix. Six different composite designs were produced by hand lay-up method, including glass fiber reinforced plastic (GFRP), coconut coir reinforced plastic (CCRP), human hair reinforced plastic (HHRP), glass - coconut coir - human hair- glass hybrid composite (GCHGRP), coconut coir-glass-human hair-coconut coir hybrid composite (CGHCRP), and human hair-coconut coir-glass-human hair hybrid composite (HCGHRP). The results showed that, whereas CCRP had the highest tensile load capacity, HCGHRP had the best flexural strength. Furthermore, when compared to other composites, HCGHRP exhibited significant impact strength values [46]. In another study, Selvan et al. used the hand lay-up technique to produce five different composite designs reinforced with jute fiber and human hair fiber with varying ratios. As a matrix material, epoxy resin was used. The mechanical properties were investigated, and the results showed that increasing the human hair content enhanced the tensile, flexural, double shear, and impact properties [47].

As a consequence of reviewing the literature on these investigations, the goal of this research is to develop hybrid composite materials reinforced with waste textile materials that can be used in substitute of the most commonly used E-glass reinforced composite materials. When considering the used waste groups, the fact that a study in which polyamide-based pantyhose waste was evaluated as a reinforcement material had not been done before reveals the study's originality, while utilizing cotton, a fiber that consumes a high amount of chemicals, water, and energy during its production, and the use of human hair which is sent from barber shops to landfills in almost every country, despite having very high mechanical properties, shows the contribution of the study to sustainability.

2. MATERIAL AND METHOD

2.1 Material

In this study, four diverse textile materials (E-glass fabric, waste denim, waste pantyhose and human hair) are used as reinforcement materials. E-glass (supplied by Omnis Kompozit) is in the form of plain-woven fabric and technical properties are given in Table 1. Preconsumer waste denim fabric (supplied by Calik Denim) and postconsumer waste pantyhose (supplied by consumers) are used in fiber form. Undyed human hair obtained from a male barber is cut into 10-30 mm lengths and used. A microscope (Zeiss, Primo Star) is used to measure the diameter and length of the waste fibers used. The average diameters of waste cotton, polyamide, and human hair are 18.7 ± 1 μm, 19.7 ± 0.7 μm, and 70 ± 5 μm, respectively, while the average lengths of cotton and polyamide fibers are 20-40 mm and 30-50 mm, respectively. Denim is comprised entirely of cotton fibers, whereas pantyhose is made up of 85% polyamide and 15% elastane. The matrix system consists of an epoxy resin (F-1564, Fibermak) and a hardener (F-3486, Fibermak). The technical properties of the resin system are given in Table 2. They are mixed in a ratio of 3:1.

Table 1. Technical properties of E-glass fabric

Basis Weight (g/m^2)	**Warp x Weft Densities (epc x ppc)***	**Thickness (mm)**	**Warp Yarn Count (Tex)**	**Weft Yarn Count (Tex)**
300	4 x 3	0.37	600	850

* epc: ends per cm and ppc: picks per cm

Table 2. Technical properties of resin system.

	Density (25 °C) [g/cm^3]	**Viscosity (25 °C) [cps]**	**Epoxide value [Eq/kg]**	**Amine value [Eq/kg]**
Epoxy resin	1.1-1.2	1250–1450	5.80 - 6.05	-
Hardener	1.0	10–20	-	8.55 - 9.30

Figure 1. (a) Feeding and (b) output unit of rag pulling machine, (c) feeding and (d) output unit of carding machine

2.2 Method

Preparation of waste reinforcement materials

Waste denim fabrics and waste polyamide pantyhose are turned into fiber form by going through a rag pulling machine (Balkan Machine – Type: DT 10) (Figure 1(a) - (b)) separately before composite material production. After that, these fiberized materials are put into the carding machine (Mesdan – Type: 337A) (Figure 1(c) - (d)), which produces an aligned web form. In addition, the other waste reinforcement material human hair is washed, dried and after that cut into lengths of 1 to 3 cm and then fed to the carding machine to form an oriented web form.

Production of composite materials

Composite fabrication is realized by vacuum-assisted resin transfer method (Figure 2) at 90°C and structures are cured for 3 hours under 1 atm pressure. Following the application of a PVA-based releasing agent to the vacuum table, the reinforcing materials are spread onto the table and covered with peel-ply fabric, a resin-flow mesh, and a vacuum bag. The vacuum pump is used to remove surplus air before production. The produced resin is then infused into the reinforcement material, and the surplus resin is vacuumed out with the help of a vacuum pump.

Three layers of reinforcement material are used to create the composite structures. While the E-glass reinforced structure has three layers of E-glass woven fabric, the same weight of denim waste, pantyhose waste, or human hair waste is placed between two layers of E-glass fabric in hybrid composite structures (Figure 3). Table 3 shows sample codes and reinforcement types.

Physical analysis

The weights of the samples cut in specified sizes are measured with a precision balance to calculate the fiber weight ratios of the composite samples. The weights of the reinforcement materials in those dimensions are computed using the areal densities of the reinforcement materials, and the fiber weight ratio for each sample group is determined. A caliper is used to measure the thickness of the samples. By dividing the weights by the volumes of test samples whose dimensions and weights have been measured, density values are calculated.

Figure 2. Production of the composite sample by vacuum-assisted resin transfer method

Figure 3. Produced samples

Table 3. Sample codes and reinforcement types

Sample Code	Reinforcement layer I	Reinforcement layer II	Reinforcement layer III
GGG	E-glass fabric	E-glass fabric	E-glass fabric
GDG	E-glass fabric	Denim waste	E-glass fabric
GPG	E-glass fabric	Pantyhose waste	E-glass fabric
GHG	E-glass fabric	Human hair waste	E-glass fabric

Mechanical Analysis

Charpy impact resistance

The Charpy impact test is carried out using the Devotrans impact tester (Model: DVT CD OK) in compliance with BS EN ISO 179: 1997 (Sample dimensions: 127×12.7 mm). The samples have a notch cut out in the center, and 12 joule impact energy is applied to the notched samples. Three specimens in the 0° direction and three specimens in the 90° direction are tested from each sample group, and the mean values are presented along with standard deviation values.

Drop-weight impact resistance

The drop-weight impact test performed with the BESMAK impact tester (custom-made) is carried out following the ASTM D7136 standard (sample dimensions: 89×55 mm). According to the potential energy law, the impact is adjusted to 20 joules by altering the height of the striker (diameter: 16 mm, weight: 41 kg). Each sample group is given five measurements, and the mean results are given by standard deviation values.

Flexural strength

The ASTM D790-10 standard (sample dimensions: 136x20 mm) is used to conduct the flexural strength test with the Shimadzu universal testing machine (AG-IS Series). The crosshead speed is set at 6 mm/min. Three specimens in the 0° direction and three specimens in the 90° direction are tested from each sample group, and the mean values are presented along with standard deviation values.

Tensile strength

Tensile testing is carried out with the use of a Shimadzu universal testing machine (AG-IS Series), in accordance with the ASTM D638 standard (sample overall length: 115 mm, the width of narrow section: 6mm). Six measurements are taken for each sample group (3 specimens at 0° direction and 3 specimens at 90° direction), with the crosshead speed set to 3 mm/min. The standard deviation values are included alongside the tensile strength mean values.

Statistical Analysis

The statistical significance of the physical and mechanical test results comparisons is investigated using the Minitab 16 software program and the 2-sample t-test method at a 95% confidence interval. The results are evaluated according to the p-value and those below 0.05 are expressed as statistically significant.

3. RESULTS AND DISCUSSION

3.1 Physical Analysis

Table 4 shows the thickness, density, and fiber weight ratios of composite samples. The fiber weight ratios of the waste-reinforced samples are comparable (38-44%), while the fiber weight ratio of the 3-ply E-glass fabric-reinforced sample (65%) is significantly higher than the others. When the fiber weight ratios of the GGG sample are compared to those of the GDG, GPG, and GHG hybrid samples statistically, it is discovered that the differences are all statistically significant (p values are 0.014, 0.000, and 0.017, respectively), whereas the differences in the fiber weight ratios of the hybrid samples (except for the GDG-GHG comparison) are not. This scenario is hypothesized to be caused by two factors. E-glass has a hydrophobic surface and this reduces its liquid affinity [48]. In addition, since the middle layer is a fiber layer in waste-reinforced sandwich structures, it has much more gaps than the E-glass woven fabric reinforced sample. These gaps allow the material to absorb more resin and reduce the fiber weight ratio. When the waste-reinforced samples are compared, it is discovered that the fiber weight ratio of the structure with the human hair inter layer (GHG) is greater than the others. The reason is that, whereas the inside section of human hair is hydrophilic, the surface is hydrophobic [49].

The GGG sample has a much lower thickness (p values of GGG-GDG, GGG-GPG and GGG-GHG thickness comparisons are 0.034, 0.017 and 0.001, respectively) than the others because the E-glass fiber absorbs less resin than the reinforcement materials in the other samples. Furthermore, the high density of the E-glass fiber (2.56 g/cm^3) and the higher fiber weight ratio in the GGG sample compared to the other samples resulted in a higher density.

Table 4. Physical properties of composite samples

Sample Code	Thickness ± SD (mm)	Density ± SD (g/cm^3)	Fiber Weight Ratio ± SD (%)
GGG	0.93 ± 0.06	1.47 ± 0.08	0.65 ± 0.03
GDG	1.95 ± 0.19	1.21 ± 0.08	0.39 ± 0.03
GPG	1.69 ± 0.14	1.24 ± 0.05	0.40 ± 0.02
GHG	1.70 ± 0.08	1.16 ± 0.09	0.44 ± 0.02

3.2 Mechanical Analysis

Charpy impact resistance

Figure 4 shows the Charpy impact resistance values of composite samples taken at 0° and 90° directions. The excellent impact resistance of the E-glass fiber is one of its most distinguishing characteristics [50]. The impact resistance of the composite sample with a human hair layer between two E-glass fabrics (GHG) is higher than that of the E-glass fabric reinforced sample (GGG), according to the results. It has been observed in several research in the literature that hybridizing glass fiber with natural fibers at particular rates increases the material's impact resistance. The high elongation value of the additional natural fiber was cited as the cause of this condition [21, 51]. The high impact resistance obtained in the hybrid sample with the human hair interlayer can be explained by the high elongation value of human hair (dry: 20-30%, wet: up to 50%) [52], which is a form of wool. Additionally, in a study conducted by Saiman et al. (2013), the mechanical properties of composites reinforced with yarns of varying yarn counts were investigated, and it was revealed that increasing yarn diameter resulted in a significant increase in the impact strength of the composite material. One of the reasons for the high impact resistance obtained from the GHG sample may be that the diameter of the human hair used in this study is approximately three times that of the other waste fibers [53].

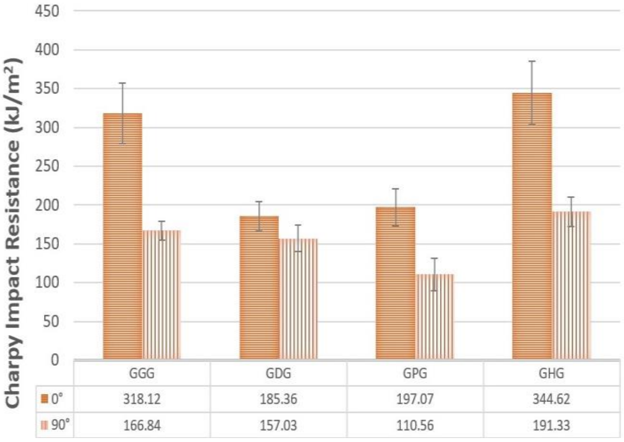

Figure 4. Charpy impact resistance results

Waste denim (GDG) and waste pantyhose (GPG) reinforced composite samples have fairly similar and lowest impact resistance values at 0° direction (p-value for 0° and 90° directions are 0.085 > 0.05 and 0.015, respectively). Furthermore, the impact resistance values of samples collected from 0° direction are higher than those of samples taken from 90° direction. The 0° direction corresponds to the plain-woven E-glass fabric's warp direction and the oriented directions of the waste fiber webs, therefore this is an expected result. The statistical significance of this situation is also investigated using the 2-sample t test, and the results obtained from the 0° and 90° directions of each of the GGG, GDG, GPG, and GHG samples are compared with each other, yielding p values of 0.005, 0.025, 0.009, and 0.012, respectively.

Drop-weight impact resistance

Structures having stiff surfaces in their outer layers and more hollow and shock-absorbing layers in their inner layers are known to withstand mechanical loads better [54, 55]. In the drop-weight impact test, the load is applied to the fabric layer first, then to the fiber layer in between, resulting in an increase in the amount of energy absorbed. Consistent with this information, the samples containing waste textile fiber webs absorb more energy than the GGG sample, as shown in Table 5.

The acquired results are similar to the Charpy impact test results and show that the GHG sample absorbs more energy than the others. This is thought to be due to the fact that the elongation value of human hair is quite high compared to other fibers [52]. It has also been statistically proven by a 2-sample t test, except for the GDG sample. The p-value in the analysis examining the differences in the absorbed energies of the GHG and GDG samples is found as 0.106, indicating that there is no statistically significant difference between them and the p values of other comparisons (GHG-GGG and GHG-GPG) are found as 0.014 and 0.049, respectively. Furthermore, in a study examining the mechanical properties of hybrid composite structures made of coconut fiber, human hair fiber, and glass fiber, it was discovered that the impact resistance of the hybrid composite structure made up of a high percentage of human hair fiber was greater than the others, supporting the result [46].

Table 5. The drop-weight impact strength test results

Sample Code	Maximum load ± SD (kN)	Absorbed energy ± SD (J)	Maximum load ± SD (kN)
GGG	2.54 ± 0.08	9.88 ± 0.62	11.73 ± 1.07
GDG	2.64 ±0.09	13.67 ± 1.01	17.00 ± 1.73
GPG	2.38 ± 0.08	12.61 ± 1.83	14.93 ± 1.28
GHG	2.46 ± 0.11	15.52 ± 1.79	22.17 ± 2.01

Flexural strength

Figure 5 shows the flexural strength of the samples taken in the 0° and 90° directions. Higher values are obtained with samples taken from the 0° direction, as is the case with impact strength. The statistical significance of this situation is also reviewed using the 2-sample t test, and the results from the 0° and 90° directions of each of the GGG, GDG, GPG, and GHG samples are compared, achieving p values of 0.001, 0.020, 0.000, and 0.000, respectively. When the strength values are examined, it is discovered that the three layers of E-glass fabric reinforced sample (GGG) has the lowest value, while the denim waste (GDG) and pantyhose waste (GPG) reinforced structures have the greatest values.

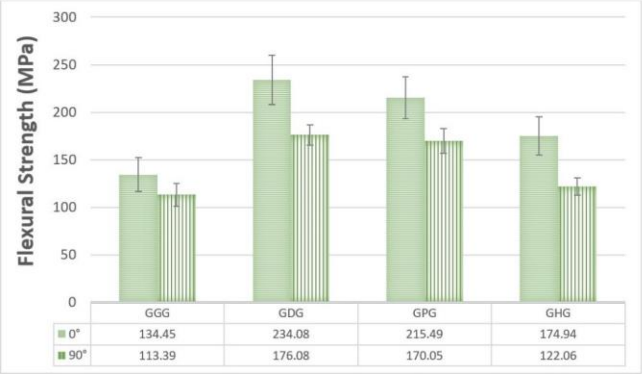

Figure 5. Flexural strength test results

The fiber weight ratio of the GGG sample is much higher than that of the other samples, as shown in Table 3, indicating that the epoxy resin ratios of the hybrid composite samples are higher than that of the GGG sample. Brittle materials have greater flexural strength [53]. As it is known that increasing the cured epoxy ratio increases the brittleness of the material, higher flexural strength values of hybrid composites are expected. Besides this, Shibata et al. (2015) noted that increasing the length of the fiber used in fiber-reinforced polymer composites enhanced the flexural strength of the composite material. The fibers obtained from the denim and pantyhose wastes used in this study are known to be longer than the length of human hair. This is assumed to be the reason the GDG and GPG samples have higher bending strength values than the GHG sample [56].

Tensile strength

Figure 6 shows the tensile strength values of composite samples. The samples reinforced with three layers of E-glass fabric (GGG) show the highest tensile strength values in both directions when compared to the hybrid samples reinforced with waste materials. This circumstance is also statistically analyzed, and it is demonstrated that there is a significant difference (p: 0.000 < 0.05) between the tensile strength values of the GGG samples and the tensile strength values of the hybrid samples obtained from both directions. The GGG sample's middle layer is made of E-glass plain-woven fabric, whereas the other three samples are in the shape of fiber webs. The tensile strength of woven constructions is increased because the intersection of the yarns generates a stable situation in the structure [55]. Plain woven textiles, which have the most warp/weft interlaces per unit area, are more resistant to in-plane shear movements, making them good reinforcing materials [57].

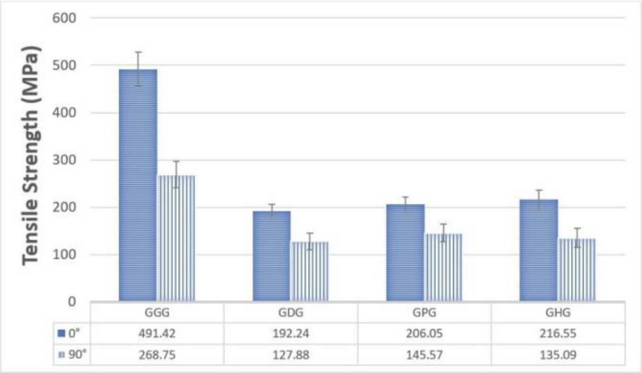

Figure 6. Tensile strength test results

According to the literature, the tensile strength of composite materials is mostly related to the tensile strength of the fiber utilized and increases as the number of glass layers increases [50]. This could explain why the GGG sample has such a high tensile strength value. Besides that, in a study comparing the mechanical properties of coconut, human hair, and glass fiber-reinforced hybrid composite structures with those of glass fiber-reinforced composite structures, it was discovered that glass fiber-reinforced composite has the highest tensile strength [46]. This information from the literature corroborates the outcome.

4. CONCLUSION

Textile-reinforced composite materials hybridized with various textile wastes (denim, pantyhose, and human hair) are produced in this study, and their mechanical properties are compared to those of E-glass fabric-reinforced composite. Because E-glass is the most commonly used fiber in composite production, it is chosen as the control sample. Pantyhose, which has a very short lifespan and cannot be given to someone else for reuse, denim, which has a large environmental impact both during cotton cultivation and fabric production, and human hair, which is sent to landfills every day by hairdressers and barbers, are chosen as textile wastes to be evaluated for this purpose. The key findings are listed below.

- Textile waste-reinforced hybrid composite samples have much lower densities than E-glass fabric-reinforced sample.
- The impact (Charpy and drop-weight) strength values of the hybrid composite samples reinforced with human hair are higher than those of the other samples, which could be attributed to the larger diameter of human hair compared to other waste fibers.

- The flexural strength values of the textile waste-reinforced hybrid composite samples are significantly greater than those of the E-glass fabric-reinforced samples; additionally, the highest strength values are obtained with the samples reinforced with denim and pantyhose wastes, which could be credited to the longer length of these fibers.
- The strength of samples taken from the 0° direction is higher in all mechanical tests.
- However, the tensile strength values of textile waste-reinforced hybrid composites are significantly lower than those of the E-glass reinforced sample.

These findings indicate that waste textile-reinforced hybrid composite materials can be used as an alternative to E-glass reinforced composites when tensile strength is not required and bending and impact strength are important. The significance of various waste groups is revealed by assessing the waste of pantyhose, which has never been used as a reinforcement material in the literature, as well as human hair, which is not commonly used in polymer-based composites. In our world of diminishing natural resources, it is expected that the findings of this study will serve as a guide for future research and shed light on the recycling studies of many waste groups that are currently not recycled.

REFERENCES

1. Yalcin-Enis I., Kucukali-Ozturk M., Sezgin H. 2019. Risks and management of textile waste. In: Gothandam K., Ranjan S., Dasgupta N., Lichtfouse E. (eds) Nanoscience and Biotechnology for Environmental Applications. Environmental Chemistry for a Sustainable World, vol 22. Springer, Cham.
2. Echeverria CA, Handoko W, Pahlevani F, Sahajwalla V. 2019. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. *Journal of Cleaner Production* 208, 1524-1536.
3. Kamble Z, Behera BK. 2021. Sustainable hybrid composites reinforced with textile waste for construction and building applications. *Construction and Building Materials* 284, 122800.
4. Lu JJ, Hamouda H. 2014. Current status of fiber waste recycling and its future. *Advanced Materials Research* 878, 122–131.
5. Wang Y. 2010. Fiber and Textile Waste Utilization. *Waste and Biomass Valorization* 1, 135–143.
6. Egan J, Salmon S. 2022. Strategies and progress in synthetic textile fiber biodegradability. *SN Applied Sciences* 4(22). https://doi.org/10.1007/s42452-021-04851-7.
7. Zhang Y, Liu X, Xiao R, Yuan Z. 2015. Life cycle assessment of cotton T-shirts in China. *The International Journal of Life Cycle Assessment* 20, 994–1004.
8. Hawley JM. Textile recycling: a system perspective. In: Wang, Y. (ed.) Recycling in Textiles, pp. 7–24. Woodhead Publishing, 2016, Cambridge
9. Kotliar A. 199. Wood-like properties from carpet and textile fibrous waste: mitigating the coming landfill crisis. *Polymer-Plastics Technology and Engineering* 38(3), 513–531.
10. Briga-Sá A, Nascimento D, Teixeira N, Pinto J, Caldeira F, Varum H, Paiva A. 2013. Textile waste as an alternative thermal insulation building material solution. *Construction and Building Materials* 38, 155-160.
11. Mishra R, Behera B, Militky J. 2014. Recycling of textile waste into green composites: Performance characterization. *Polymer Composites* 35(10), 1960-1967.
12. Hasan KMF, Horváth PG, Alpár T. 2021. Potential fabric-reinforced composites: a comprehensive review. *Journal of Materials Science* 56, 14381–14415.
13. Masood Z, Ahmad S, Umair M, Shaker K, Nawab Y, Karahan M. 2018. Mechanical behaviour of hybrid composites developed from textile waste. *Fibres and Textiles in Eastern Europe* 26, 46-52.
14. Hameed N, Sreekumar PA, Francis B, Yang W, Thomas S. 2007. Morphology, dynamic mechanical and thermal studies on poly (styrene-co-acrylonitrile) modified epoxy resin/glass fibre composites. *Composites Part A: Applied Science and Manufacturing* 38(12), 2422–2432.
15. Elanchezhian C, Ramnath BV, Hemalatha J. 2014. Mechanical Behaviour of Glass and Carbon Fibre Reinforced Composites at Varying Strain Rates and Temperatures. *Procedia Materials Science* 6, 1405–1418.
16. Radhakrishnan, S. 2017. Denim Recycling. In: Muthu, S. (eds) Textiles and Clothing Sustainability. Textile Science and Clothing Technology. Springer, Singapore. https://doi.org/10.1007/978-981-10-2146-6_3
17. Yousef S, Tatariants S, Tichonovas M, Sarwar Z, Jonuškienė I, Kliucininkas L. 2019. A new strategy for using textile waste as a sustainable source of recovered cotton. *Resources Conservation & Recycling* 145, 359-369.
18. Pensupa N, Leu SY, Hu Y, Du C, Liu H, Jing H, Wang H, Lin CSK. 2017. Recent Trends in Sustainable Textile Waste Recycling Methods: Current Situation and Future Prospects, In: Lin C. (eds) Chemistry and Chemical Technologies in Waste Valorization. Topics in Current Chemistry Collections. Springer, Cham.
19. Yousef S, Tatariants M, Tichonovas M, Kliucininkas L, Lukosiute SI, Yan L. 2020. Sustainable green technology for recovery of cotton fibers and polyester from textile waste. *Journal of Cleaner Production* 254, 120078.
20. Baydar G, Ciliz N, Mammadov A. 2015. Life cycle assessment of cotton textile products in Turkey. *Resources, Conservation and Recycling* 104, 213-223.
21. Giridharan R, Jenarthanan MP. 2019. Preparation and characterisation of glass and cotton fibers reinforced epoxy hybrid composites. *Pigment & Resin Technology* 48(4), 272-276.
22. Hasret F, Agac S. 2021. A sustainable design example: Evaluation of pantyhose with bricolage and deconstruction method. *Global Journal of Arts Education* 11(1), 71-88.
23. Guler S. 2018. The effect of polyamide fibers on the strength and toughness properties of structural lightweight aggregate concrete. *Construction and Building Materials* 173, 394-402.
24. Jeon JK, Kim W, Jeon CK, Kim JC. 2014. Processing and mechanical properties of macro polyamide fiber reinforced concrete. *Materials* 7, 7634-7652.
25. Jeon JK, Kim W, Kim GY, Jeon CK. 2016. Polyamide fiber reinforced shotcrete for tunnel application. *Materials* 9(3), 163.
26. Nieto SPR, Giraldo ES, Pedrao D, Calderon G, Valbuena GCC. 2014. Influence of nylon on the tensile strength of a polymer matrix composite material. *Tecciencia* 9(16), 78-84.
27. Gupta A. 2014. Human Hair ‘‘Waste’’ and Its Utilization: Gaps and Possibilities. *Journal of Waste Management* 2014, 498018.
28. Nanda BP, Satapathy A. 2020. Processing and thermal characteristics of human hair fiber-reinforced polymer composites. *Polymers and Polymer Composites* 28(4), 252-264.

29. Butt WA, Mir BA, Jha JN. 2016. Strength behavior of clayey soil reinforced with human hair as a natural fibre. *Geotechnical and Geological Engineering* 34, 411-417.

30. Jain D, Kothari A. 2012. Hair fibre reinforced concrete. *Research Journal of Recent. Sciences* 1, 128-133.

31. Vengatesan KJ, Prasanth T, Swagath Kumar VKS, Suresh K, Chokkalingam P. 2017. Study on mechanical properties and structural analysis of human hair fiber reinforced epoxy polymer. *International Journal of Advanced Research in Basic Engineering Science and Technology* 3, 754-759.

32. Temmink R, Baghaei B, Skrifvars M. 2018. Development of biocomposites from denim waste and thermoset bio-resins for structural applications. *Composites Part A: Applied Science and Manufacturing* 106, 59-69.

33. Hassani P, Soltani P, Ghane M, Zarrebini M. 2021. Porous resin-bonded recycled denim composite as an efficient sound-absorbing material. *Applied Acoustics* 173, 107710.

34. Oztemur J, Sezgin H, Yalcin-Enis I. 2021. Design of an impact absorbing composite panel from denim wastes and acrylated epoxidized soybean oil based epoxy resin. *Tekstil ve Konfeksiyon* 31(3), 229 – 234.

35. Meng X, Fan W, Mahari WAW, Ge S, Xia C, Wu F, Han L, Wang S, Zhang M, Hu Z, Ma NL, Le QV, Lam SS. 2021. Production of three-dimensional fiber needle-punching composites from denim waste for utilization as furniture materials. *Journal of Cleaner Production* 281, 125321.

36. Sezgin H, Kucukali-Ozturk M, Berkalp OB, Yalcin-Enis I. Design of composite insulation panels containing 100% recycled cotton fibers and polyethylene/polypropylene packaging wastes. *Journal of Cleaner Production* 304, 127132.

37. Meng X, Fan W, Ma Y, Wei T, Dou H, Yang X, Tian H, Yu Y, Zhang T, Gao T. 2020. Recycling of denim fabric wastes into high-performance composites using the needle-punching nonwoven fabrication route. *Textile Research Journal* 90(5-6), 695-709.

38. Islam S, Messiry ME, Sikdar PP, Seylar J, Bhat G. 2020. Microstructure and performance characteristics of acoustic insulation materials from post-consumer recycled denim fabrics. *Journal of Industrial Textiles,* https://doi.org/10.1177/1528083720940746.

39. Lu L, Fan W, Meng X, Liu T, Han L, Zhang T, Dong J, Yuan L, Tian H. 2021. Modal analysis of 3D needled waste cotton fiber/epoxy composites with experimental and numerical methods. *Textile Research Journal* 91(3-4), 358-372.

40. Zonatti WF, Guimaraes BMG, Duleba W, Ramos JB. 2015. Thermoset composites reinforced with recycled cotton textile residues. *Textiles and Clothing Sustainability* 1, https://doi.org/10.1186/s40689-014-0001-7.

41. Baccouch W, Ghith A, Yalcin-Enis I, Sezgin H, Miled W, Legrand X, Faten F. 2022. Investigation of themechanical, thermal,and acoustical behaviorsof cotton, polyester,and cotton/polyester nonwoven wastes reinforced epoxy composites. *Journal of Industrial Textiles* 51(6), 876 –899.

42. Verma A, Singh V. 2019. Mechanical, microstructural and thermal characterization of epoxy-based human hair–reinforced composites. *Journal of Testing and Evaluation* 47(2), 1193-1215.

43. Selvakumar K, Meenakshisundaram O. 2019. Mechanical and dynamic mechanical analysis of jute and human hair-reinforced polymer composites. *Polymer Composites* 40(3), 1132-1141.

44. Ansari AA, Dhakad SK, Agarwal P. 2020. Investigation of mechanical properties of sisal fibre and human hair reinforced with epoxy resin hybrid polymer composite, *Materials Today: Proceedings* 26(2), 2400-2404.

45. Balachandar M, Ramnath BV Kumar SA, Sankara GS. 2019. Experimental evaluation on mechanical properties of natural fiber polymer composites with human hair. *Materials Today: Proceedings* 16(2), 1304-1311.

46. Senthilnathan D, Gnanavel Babu A, Bhaskar GB, Gopinath KGS. 2014. Characterization of glass fibre – coconut coir– human hair hybrid composites. *International Journal of Engineering and Technology* 6(1), 75-82.

47. Panneer Selvan S, Jaiganesh V, Selvakumar K. 2014. Investigation of mechanical properties and optimization in drilling of jute and human hair hybrid composite, *International Conference on Advances in Design and Manufacturing*, 631-636.

48. Khan RA, Khan MA, Zaman HU, Pervin S, Khan N, Sultana S, Saha M, Mustafa AI. 2010. Comparative studies of mechanical and interfacial properties between jute and E-glass fiber-reinforced polypropylene composites. *Journal of Reinforced Plastics and Composites* 29(7), 1078-1088.

49. Popescu C, Höcker H. 2007. Hair—the most sophisticated biological composite material. *Chemical Society Reviews* 36, 1282-1291.

50. Portella EH, Romanzini D, Angrizani CC, Amico SC, Zattera AJ. 2016. Influence of stacking sequence on the mechanical and dynamic mechanical properties of cotton/glass fiber reinforced polyester composites. *Materials Research* 19(3), 542-547.

51. Zeeshan M, Ali M, Anjum AS, Nawab Y. 2019. Optimization of mechanical/thermal properties of glass/flax/waste cotton hybrid composite. *Journal of Industrial Textiles*. https://doi.org/10.1177/1528083719891420.

52. Velasco MVR, Dias TCDS, Freitas AZD, Júnior NDV, Pinto CASDO, Kaneko TM, Baby AR. 2009. Hair fiber characteristics and methods to evaluate hair physical and mechanical properties, *Brazilian Journal of Pharmaceutical Sciences* 45(1), 153-162.

53. Saiman MPB, Wahab MSB, Wahit MUB. 2013. The effect of yarn linear density on mechanical properties of plain woven kenaf reinforced unsaturated polyester composite. *Applied Mechanics and Materials* 465-466, 962-966.

54. Skrifvars M, Dhakal H, Zhang Z, Gentilcore J, Åkesson D. 2019. Study on the mechanical properties of unsaturated polyester sandwich biocomposites composed of uniaxial warp-knitted and non-woven viscose fabrics. *Composites Part A: Applied Science and Manufacturing* 121, 196–206.

55. Haery HA, Zahari R, Kuntjoro W, et al. 2014. Tensile strength of notched woven fabric hybrid glass, carbon/epoxy composite laminates. *Journal of Industrial Textiles* 43, 383–395.

56. Shibata S, Cao Y, Fukumoto I. 2005. Press forming of short natural fiber-reinforced biodegradable resin: Effects of fiber volume and length on flexural properties. *Polymer Testing* 24(8), 1005-1011.

57. Campbell FC. 2010. Structural Composite Materials. ASM International.