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Performance Assessment of Composites from Post-consumer and Post-industrial Denim Waste

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ABSTRACT

The growing population and rapid industrialization have resulted in enhanced consumption of materials. Denim is one of the most common fabrics used worldwide for trousers, with a global market of over 70 billion dollars. It has led to the production of large amount of post-consumer and post-industrial waste (PIW). The current study focusses on using this waste to develop composite materials for potential application as floor tiles. The post-industrial waste collected from a denim company and was employed to make composite tiles using thermoplastic matrices (Polyethylene and Polycarbonate). The composite tiles were fabricated in different thickness, and their mechanical performance was evaluated. The results revealed that polycarbonate is a better choice for matrix material as compared to polyethylene. The mechanical performance was higher for polycarbonate composites as compared to polyethylene composites, with a clearer and more transparent look.

Keywords: cotton, denim, waste, biocomposite, mechanical performance, thermoplastics

1. Introduction

Composite materials offer advantages of enhanced mechanical performance and reduced weight, as compared to the conventional materials. These are made of strong carry-load materials (straws, fibers, fabric etc.) which are implanted in a somewhat weaker material (binder)[1]. The stronger material is usually referred to as reinforcement and the weaker material is usually referred to as the matrix. Rigidity and strength is provided by reinforcement which aids to support the structural load. The matrix or the binder is somewhat more brittle and helps to preserve the orientation and position of the reinforcement material [2].

Composite materials play a dynamic role in engineering applications due to their superior specific strength, lightweight and stiffness. They are frequently substituting conventional massive materials. Though, in the composite industry sustained growth can only be attained if materials and procedures are sustainable, with the added considerations of environmental and economic factors. Therefore, the composites industry is becoming progressively conscious of the importance of materials selection and manufacturing, the life cycle assessment (LCA) and end of life waste management strategies [3][4].

Sustainability, eco-efficiency, industrial ecology and green solutions are the main driving factors for the development of the next generation of materials, processes and products. Bio-based polymer products and biodegradable plastics based on yearly renewable biomass feedstock and agricultural can form the foundation for a range of eco-efficient and sustainable products that can compete and capture markets presently dominated by products based completely on petroleum feedstock [5].

Natural/Bio fiber composites are evolving as a feasible alternative to glass fiber reinforced composites particularly in building and automotive product applications. Natural fiber–reinforced composites have attained commercial attraction in automotive and other industries [6]. The sustainable development is need of the time and the concept of sustainable products is given in the Figure 1.

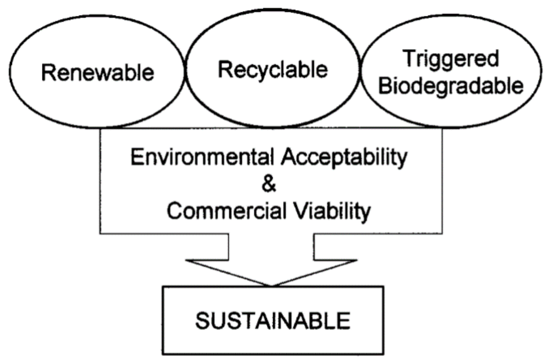


Figure 1. Concept of sustainable products

Nowadays, it is extensively known that maximum products cause impacts on the environment and inherent it all from their manufacturing processes. [7]. Therefore, environment is a powerful factor for many companies for successful business[8]. However, materials are usually viewed as functional qualities, and a mere functional product is not enough for consumers it should meet the sustainability criteria as well [9]. Textiles is the most widely used material and the average life of a clothing article is 2-3 years. Unfortunately, 84 % of the clothing ends up in landfills or incinerators.

Mishra *et al.* developed green composites using textile waste. In order to create a sustainable eco system all type of waste are needed to be utilized effectively[10]. Textile fabric waste collected from various source afterwards this textile waste was converted into fibrous material which is then converted into non-woven web and twisted strands and then used in composites. Composites with different specifications were developed and examined for different end uses. As the pp fibers concentration is increased the mechanical properties of the composite improves. The results showed that garneted fibers from waste and OE virgin cotton yarn didn’t show any significant difference thus it is safe to say that the textile waste fabric can be used in composites as reinforcement [11].

Araujo et al [12] developed composites made of Polypropylene and cotton fiber from textile waste. Surface of cellulose fibers is hydrophilic opposite to the hydrophobic polyolefin results in several problems that affect the properties and performance of the composites. Bleaching and acetylation of cellulosic fibers was done to modify the surface chemically. After these processes the acetyl groups were appeared and weakening of OH bonds [13]. There was significant loss of thermal stability caused due to chemical treatment, the composite made of treated fibers and matrix when compared with pure PP resulted in higher Young’s modulus and tensile strength.

Denim is one of the most abundantly used textile materials. The post-industrial and post-consumer waste of denim is growing at a higher rate. The waste denim fabric needs to be recycled instead of landfilling or incineration. A potential application is the use of this waste as reinforcement for the development of composite materials. As the cotton fibers have a natural origin and are annually renewable, the developed composites will serve as a sustainable materials source for various applications [14]. Eco-friendly composites from plant-based fiber (natural/biofiber) would be of great meaning to the materials world and are the novel materials in the twenty-first century, not only as a resolution to rising environmental threat but also as an answer to the ambiguity of petroleum supply [15][16].

Materials and Method

The following materials were used to carry out research.

- Post-industrial denim waste
- Polyethylene sheets
- Polycarbonate

Polyethylene sheets (PE) and polycarbonate was used as a matrix and post-industrial denim waste was used as reinforcement. The post-industrial waste (PIW) was taken from the sewing lines of a garments manufacturing unit. This material is sold as low-value waste or recycled again to make cotton in shredding plant. The post-industrial denim waste and the flow chart of process that yields this waste is shown in Figure 2.

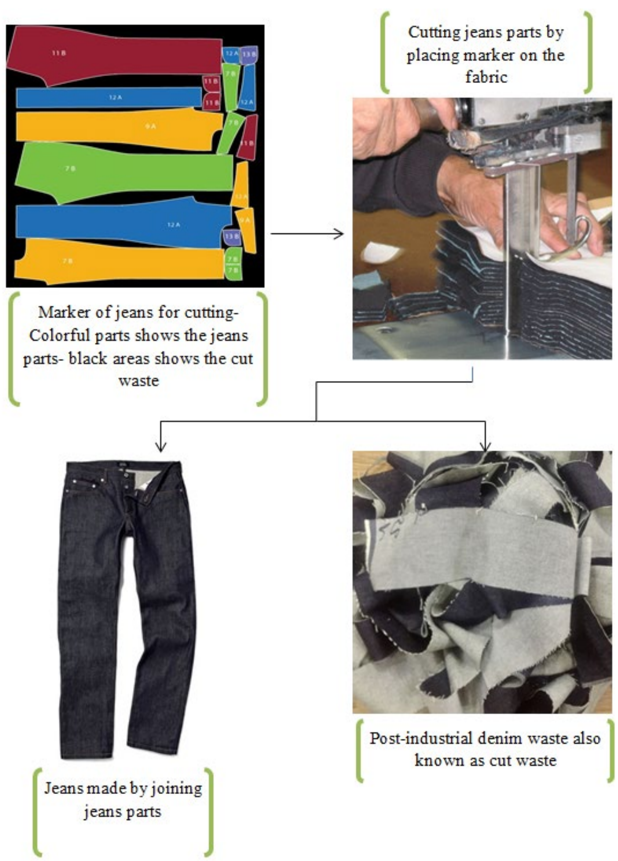


Figure 2. Flow chart of post-industrial denim waste

Table 1. Specification of post-industrial denim waste, and properties of PE and PC

PIW	Polyethylene	Polycarbonate
Weight: 12 oz./yd^2 Composition: 100% cotton + 98% cotton 2% elastane Weave: 3/1 Twill	Density: 0.88–0.96 g/cm3 Melting Point: 115–135 °C Molecular weight: 30,000–6,000,000 g/mol	Density: 1.15-1.2g/cm3 Melting point: 155°C Molecular weight: 272.29 g/mol

The specifications of the denim waste, and properties of polyethylene and polycarbonate used for the study are given in the Table 1.

The polycarbonate is thermoplastic material and can be reused just by melting and reshaping it. Here in this research post-consumer polycarbonate plates (Figure 10) were used. The waste polycarbonate was reprocessed by melting into thin sheets in compression molding machine. Basically, the idea behind using post consume PC is to close the loop of manufacturing sustainable and recycled composite tiles and test them.

The process of melting the post-consumer polycarbonate plate is demonstrated in the Figure 11 below. First of all the post-consumer polycarbonate plate was placed in the compression molding machine to convert it into thin sheet by compressing it at 190°C temperature of upper and lower plates. Compressed plates then cut into almost equal 4 parts. These sheets were used to make composite. The sheets were weighed to achieve the volume fraction percentage.

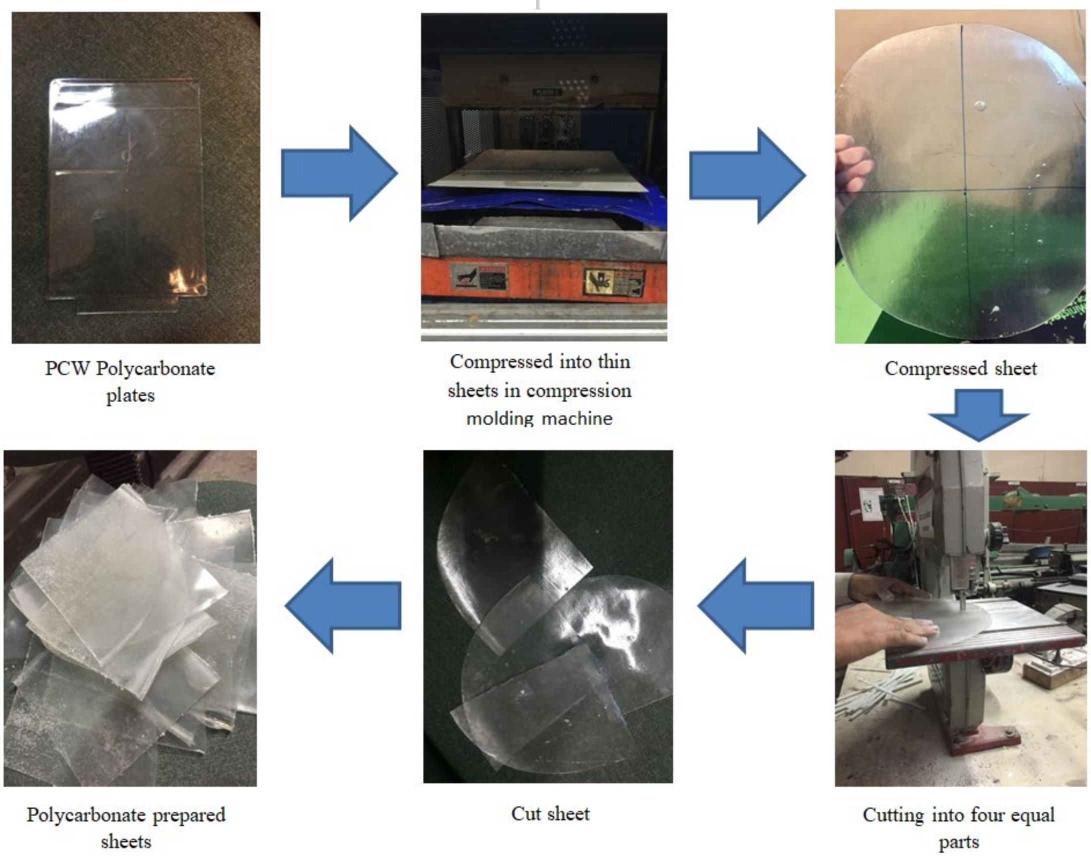


Figure 3. Process of converting post-consumer polycarbonate plates into thin sheets

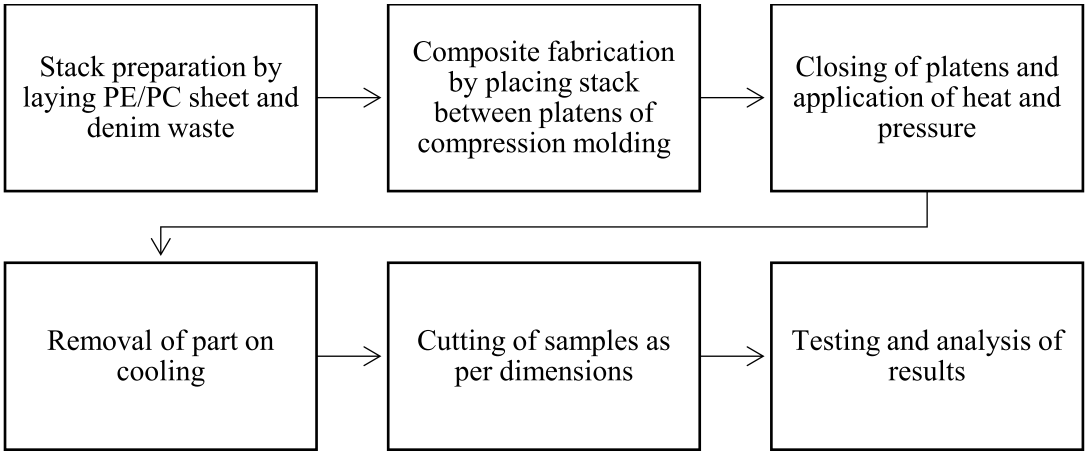


Figure 4. Methodology adopted for the composite fabrication in current study

Table 2. Details of composite samples fabricated for the study

Sample ID	Vf	Reinforcement	Matrix	Thickness (mm)
S1	64%	PIW	Polyethylene	2.7
S2	57%	PIW	Polyethylene	3
S3	52%	PIW	Polyethylene	3.3
E1	31%	PIW	Polycarbonate	2.6
E2	41%	PIW	Polycarbonate	2.4
E3	51%	PIW	Polycarbonate	2.1

2.1 Methodology

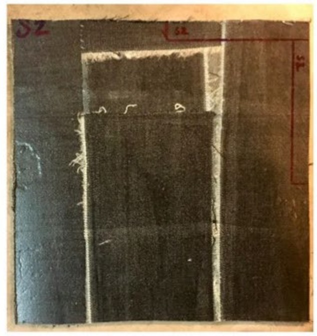
The methodology adopted for this research work is shown in Figure 4.

Composite Fabrication

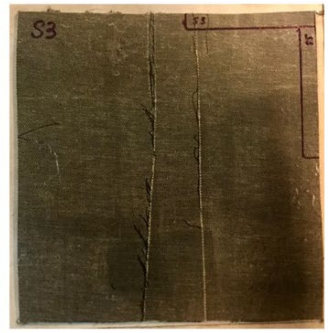
Six different composite materials were fabricated using post-industrial denim waste and two different matrices, as shown in Table 2.

The post-industrial waste was sorted size wise. Then composite plates were fabricated by stacking layers of matrix (polyethylene or polycarbonate sheets) and denim post industrial waste. After stacking the layers, samples were placed in the compression molding machine at 190˚C temperature under 2 ton pressure for 30 minutes each and then samples left in the machine until the samples cool down to room temperature. The composite samples with polyethylene and polycarbonate are shown in Figure

S1



S2



S3

E1

E2

E3

Figure 5. Composite samples with polyethylene and polycarbonate

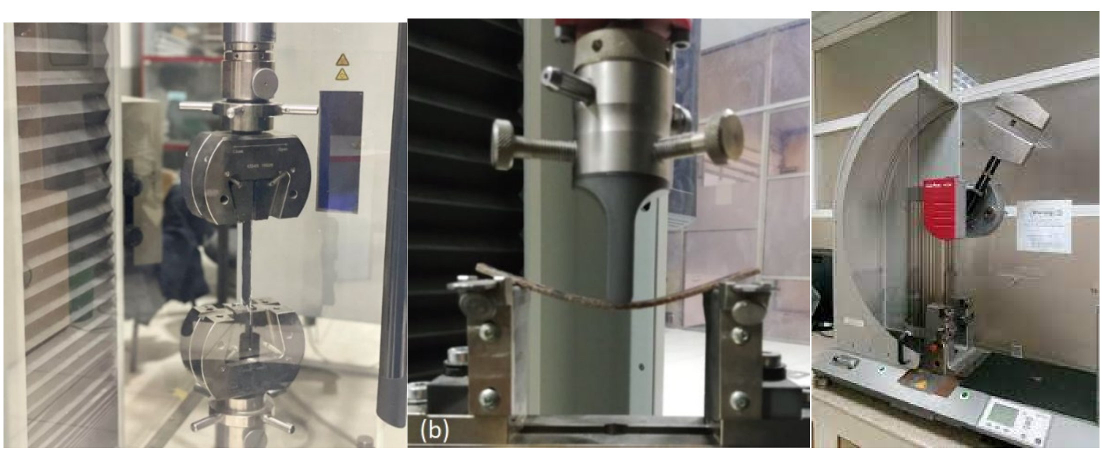


Figure 6. Equipment used for (a) tensile, (b) flexural and (c) impact testing of composites

The mechanical performance of the developed composites was investigated in terms of tensile, flexural, impact and short beam strength. The universal testing machine Z100 (Zwick/Roell, Germany) was used for tensile and flexural testing of composites, as shown in Figure 6a and 6b. The impact test was performed using Charpy impact tester HIT5.5P (Zwick/Roell, Germany) as shown in Figure 6c. The instrumented Charpy hammer monitors and records the data of force and displacement during test and plots into a curve.

Results and Discussion

Tensile properties

The tensile test was performed according to ASTM D 3039 to measure the tensile strength of polymer composite materials. This test method is used to measure the force at the composite sample break and the extent to which the composite specimen elongated. Six different types of composite samples were tested, and each type has two samples. Figure 7 showed the bar graph for tensile strength of the samples which is higher for the composites with polycarbonate that means E1, E2 and E3 requires more amount of load per unit area till it breaks, as compared to the composite sample S1, S2 and S3.

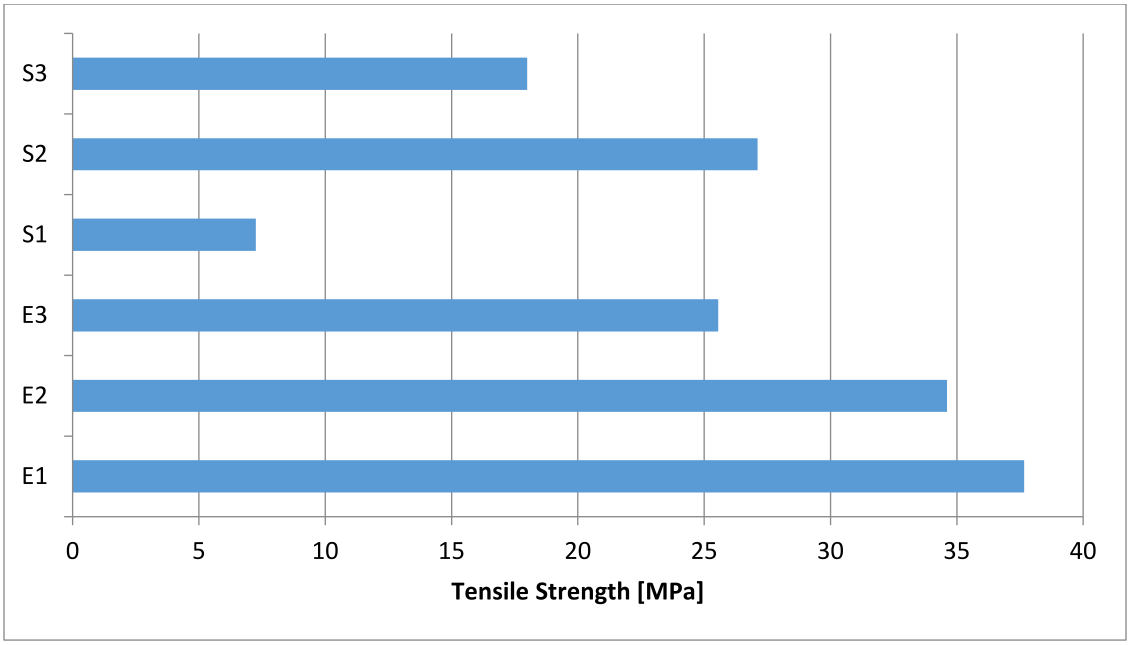


Figure 6. Tensile strength comparison of composites developed from waste

As shown in Figure 8, the samples E1-E3 break at lower strain and exhibit higher modulus compared to samples S1-S3. This little tendency to deform before fracture shows that the E1-E3 composite materials have a brittle nature. As the reinforcement material is same in all the composites, i.e. cotton, this variation is attributed mainly due to the matrix material. The polycarbonate matrix used for E1-E3 is an aromatic polymer, having brittle nature. Contrary to this, the polyethylene is an aliphatic linear polymer, and is highly ductile. This behavior of matrix has been dominant in the stress-strain curves of the resultant composites. The sample S2 showed higher elongation than all other composite samples and its ϵ at failure (%) reaches to 7.5. As the ratio of resin increase the tensile strength of material decreases. This trend was observed almost in both types of samples. On the other hand, modulus of both type of samples decreases by increasing the resin material.

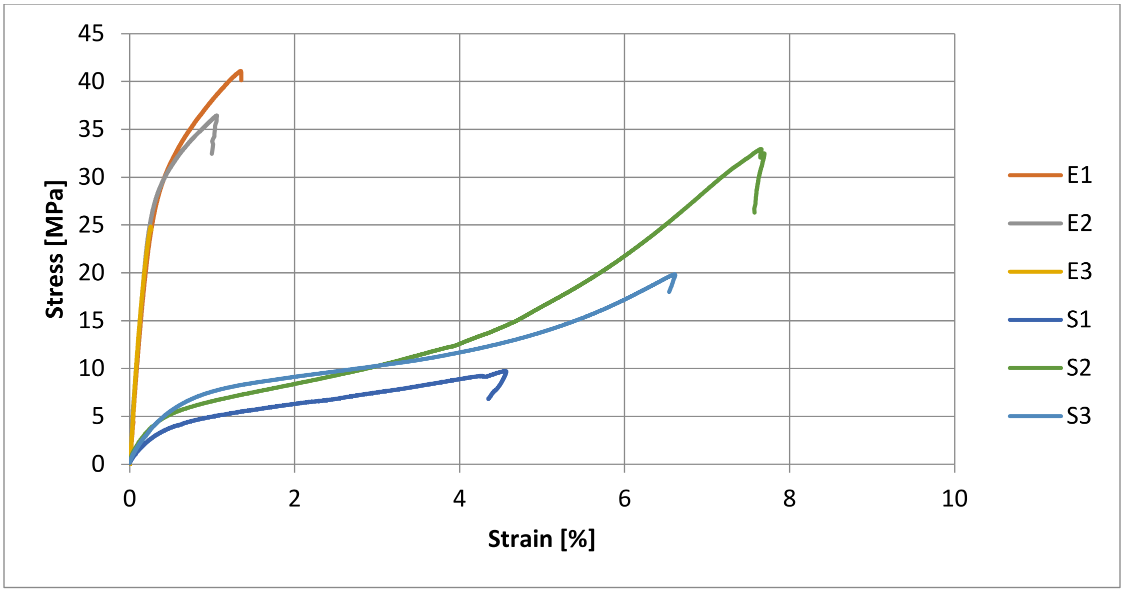


Figure 7. Strain-strain curves obtained during tensile test

Flexural properties

The ASTM D7264 testing method was used to determine the flexural stiffness and strength of polymer matrix composites, using a rectangular bar of uniform rectangular cross-section, deflected at a constant rate and supported on a two supports. This test was performed using three-point bending arrangement. Figure 9 shows the flexural strength of the samples, which is higher for the polycarbonate samples that means it is harder to bend the samples E1, E2 and E3 than S1, S2 and S3.

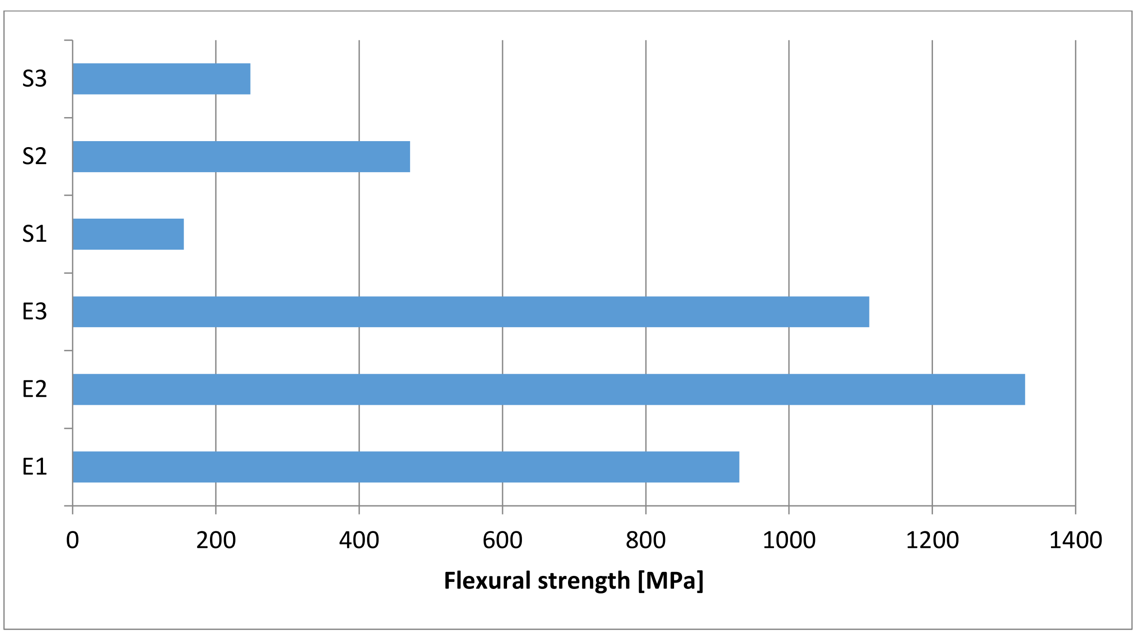


Figure 8. Flexural strength of developed composite materials

It can be observed that the sample E1, E2 and E3 have higher flexural strength value than the sample S1, S2 and S3. The mean flexural strength of E group is higher than the S group because the crosslinking of carbonates between the polymer chains makes this material stronger than the polyethylene and it does not break easily as other materials and flexural strength of material is defined as the ability of composite to resist deformation under load. Results also showed that the flexural strength of samples also decreases by increase the fraction of resin and by decreasing the reinforcement material in composite.

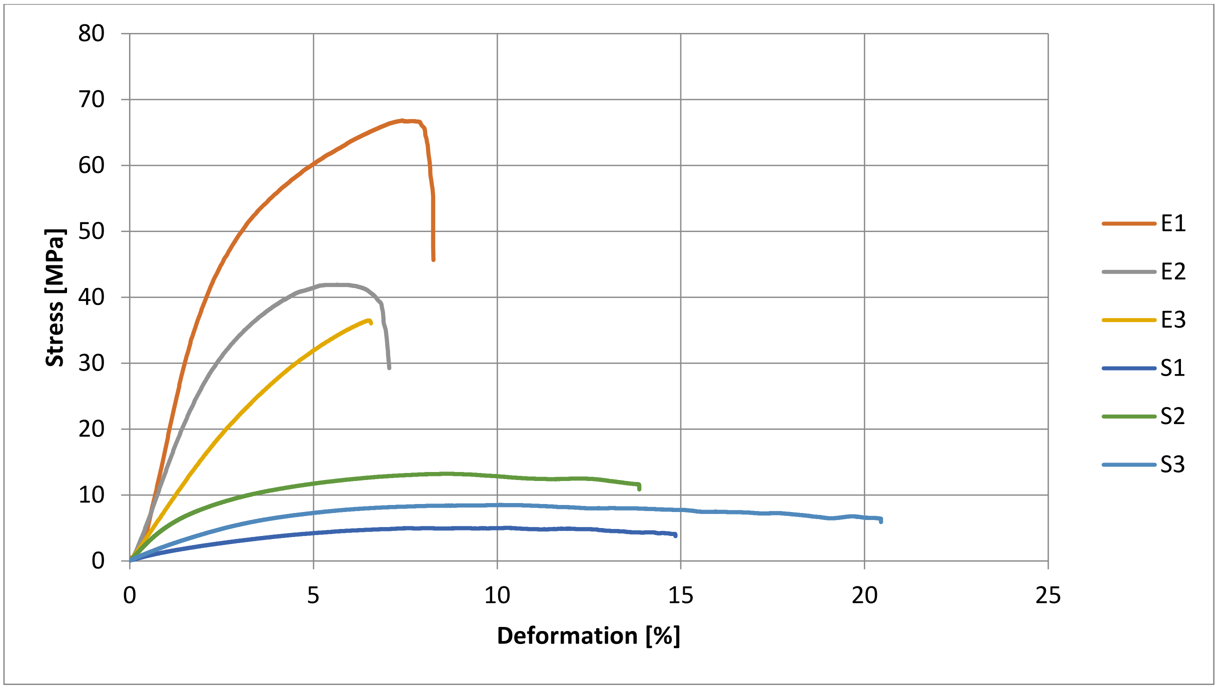


Figure 10. Load-deflection curves obtained during flexural test

As discussed earlier, polyethylene is a flexible material while polycarbonate is a brittle material. When subjected to a flexural load, the polyethylene based composite materials (S1-S3) underwent a higher mid-plane deflection under a lower stress, as compared to the polycarbonate based composite materials (E1-E3). The hypothesis is validated from the load-deflection curve shown in Figure 10. Therefore, the polycarbonate matrix composites have higher modulus, and are stiffer as compared to the polyethylene matrix composites.

Charpy Impact Properties

Composite structures can response to the impact loads and Charpy test was conducted to determine the impact damage resistance of the composite material. This test determines the impact energy absorbed by a material before its fracture (ISO 179-2). Composite materials absorb energy until its yield point and then undergo plastic deformation. The method is suitable for: acquiring different materials characteristics under impact conditions, auto detecting of the type of break, calculating fracture mechanical properties defined in ISO standards. Figure 11 shows that the polycarbonate matrix composites absorbed less energy as compared to the polyethylene matrix composites. This behavior is contrary to the tensile and flexural behavior exhibited by these composites, where polycarbonate matrix composites exhibited superior performance. The brittle materials (E1-E3), when subjected to a sudden load undergo deformation without any significant deformation. It results in less energy absorption. In case of ductile materials (S1-S3), long polymeric chains allow sufficient deformation for energy absorption before failure. Also, the variation was observed between the samples having different fiber volume fractions.

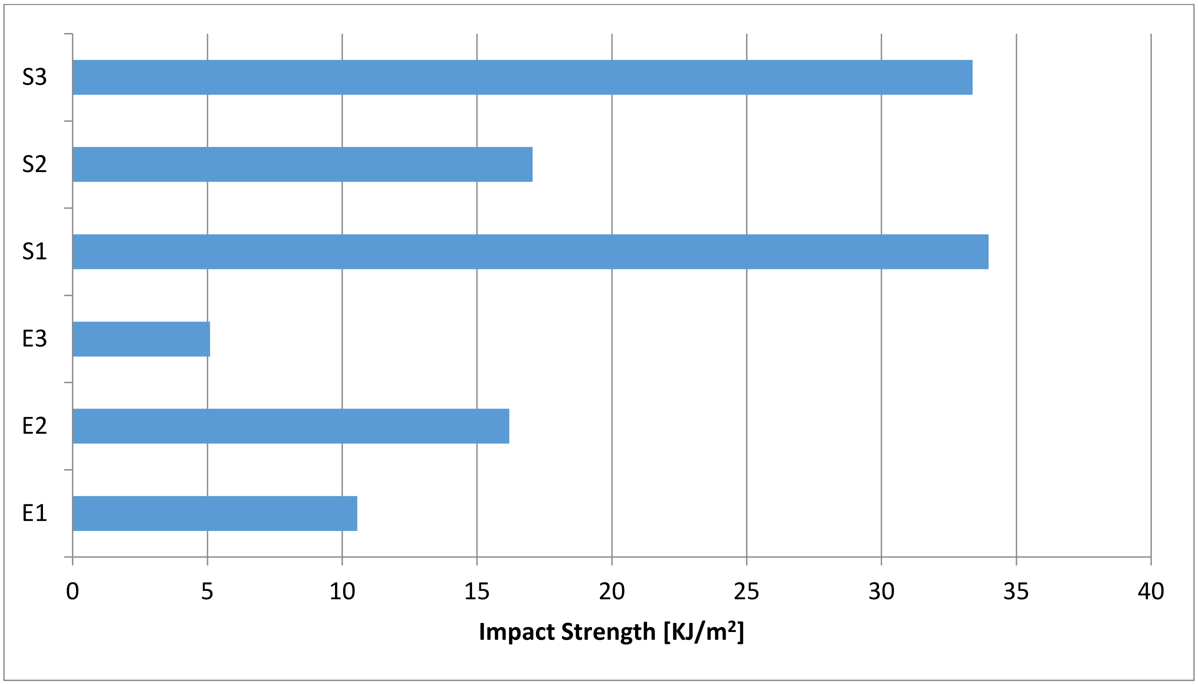


Figure 9. Charpy impact strength of composite materials

The force vs time curves obtained in impact test are shown in Figure 12 and 13. A distinct behavior was exhibited by the polycarbonate and polyethylene composites. In case of polycarbonate matrix composites (E1, E2 and E3), the force is increasing with time (neglecting the smaller peaks/deflections) up to a maximum force. Afterwards there is a sudden reduction in the force showing failure of the specimen. For polyethylene matrix composites, there is a gradual increase that deviates to non-linearity, showing plastic deformation and reaches a peak force. The specimen then gradually breaks with reduction in force.

Although the polycarbonate composites show the higher peak forces, as compared to polyethylene composites, it does not indicate their ability to absorb energy. Considering the test time, it is evident that the duration for which polyethylene composites resisted deformation was approximately ten times more than that of polycarbonate composites. Hence, the polyethylene composites absorbed higher impact energy as compared to the polycarbonate composites. . As the percentage volume of the resin increases in the samples the energy absorption capacity of the samples drops. The sample with higher reinforcement fraction absorbs more energy.

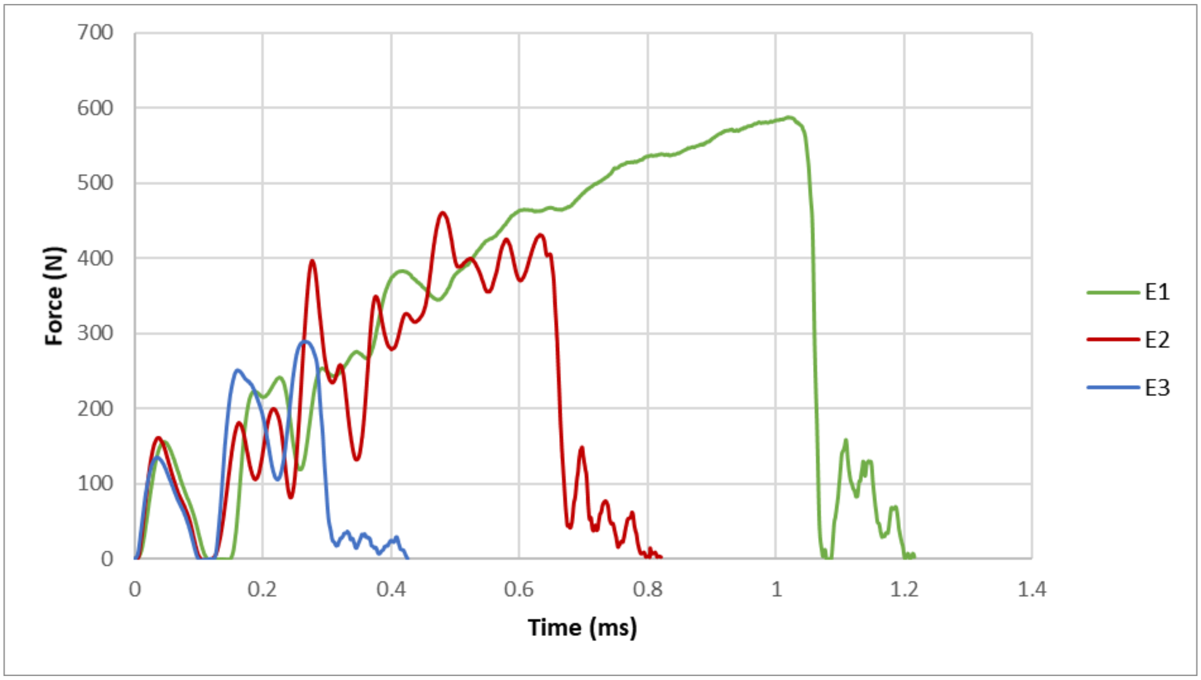


Figure 10. Force-time curves obtained during Charpy impact test for polycarbonate composites

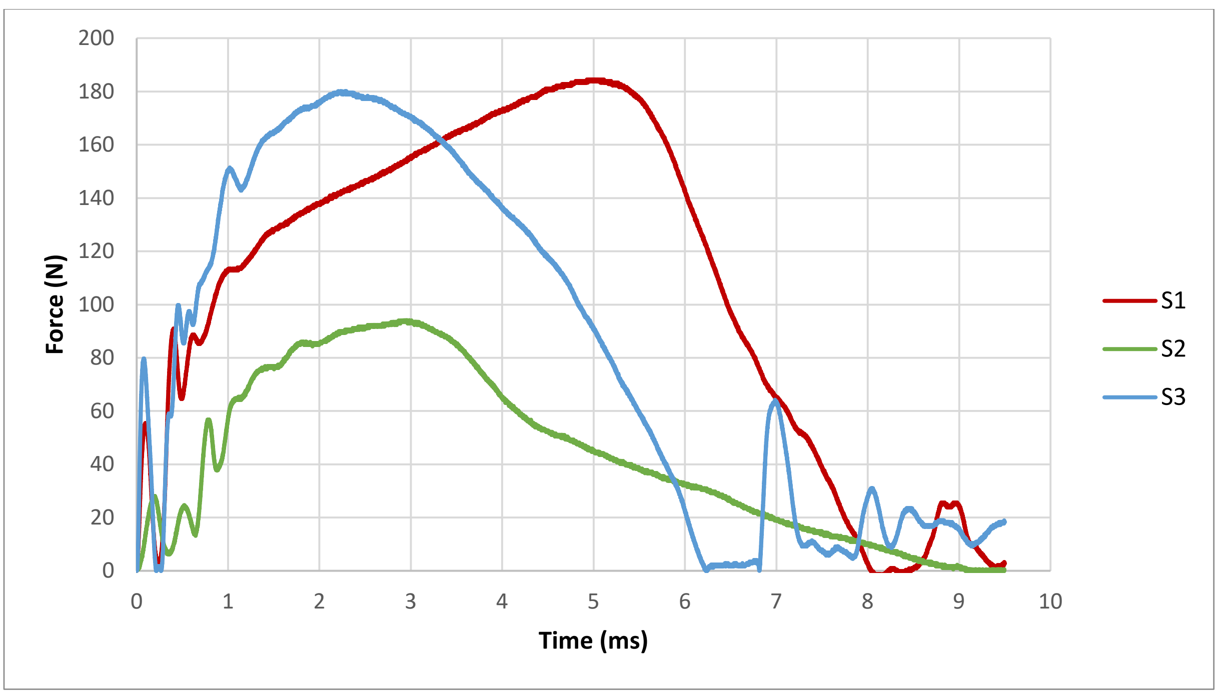


Figure 11. Force-time curves obtained during Charpy impact test for polyethylene composites

Short-Beam Strength

Short beam strength test was performed to determine the inter-laminar shear strength of parallel fibers in composite material. This test was performed according to the standard ASTM D 2344. This test method is applicable to all types of composites reinforced with parallel fibers. The sample is placed horizontal so that the fibers are parallel to the loading nose. Load is applied then to flex the sample at a speed of .05 in/min until breakage point and the force is then recorded. Calculations are done to conclude shear strength.

Figure 14 shows that the force requires as shear strength of material decreases as the fraction ratio of resin increases and reinforcement decreases. While on the other hand the polycarbonate material composite has higher strength as compared to polyethylene matrix composite.

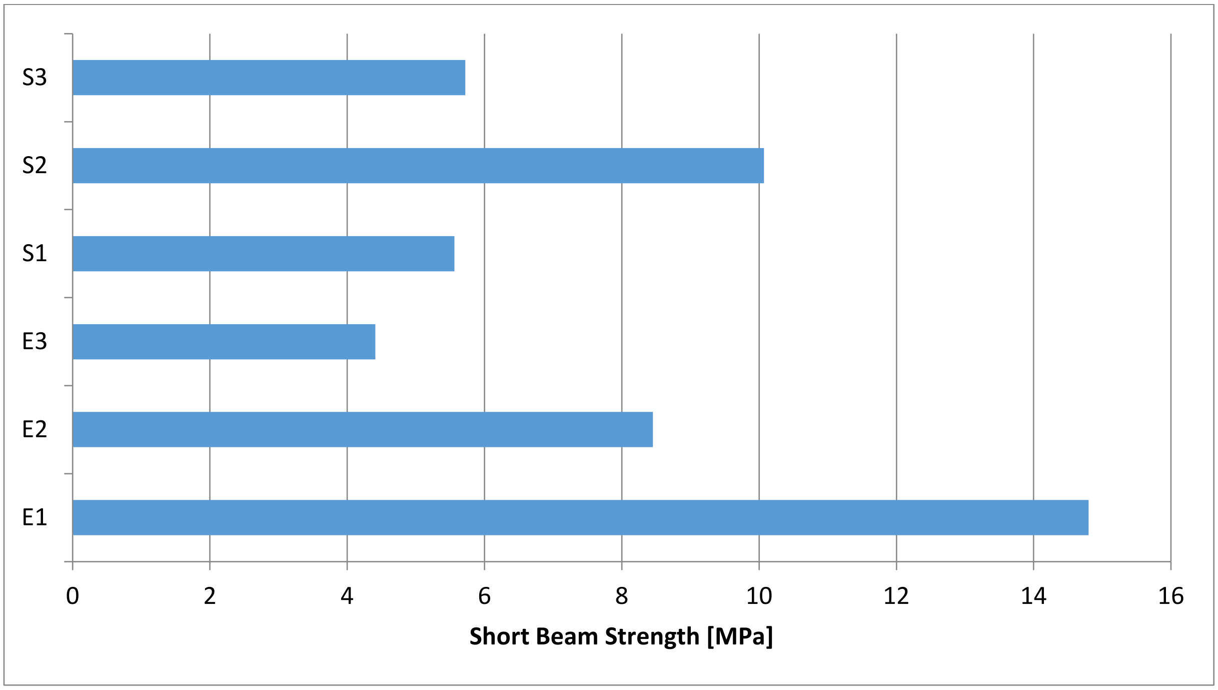


Figure 12. Short beam Strength of composites

In Figure 15 graph clearly shows that as the volume percentage of the resin increases in the Polycarbonate/denim samples E1, E2 and E3 the shear strength of the material decreases. Whereas the sample with polyethylene S1, S2 and S3 shows that the sample S2 has the highest shear strength as compared to S1 and S2.

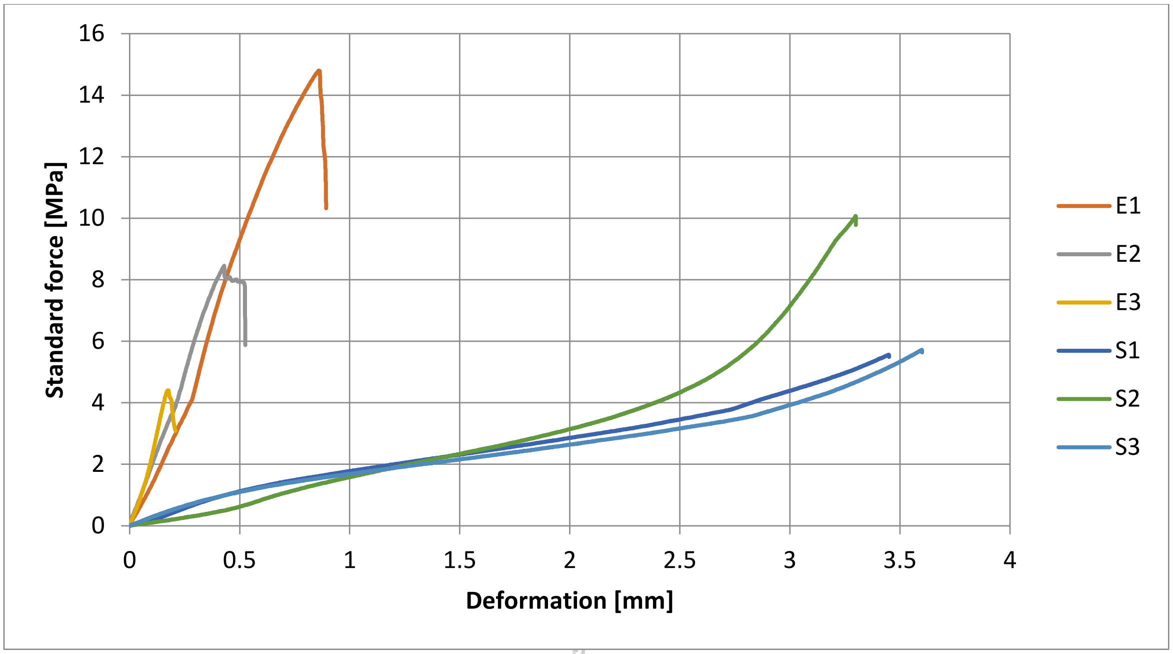


Figure 13. Short beam strength of composite materials

Conclusions

In this study, composites were developed using post-industrial denim fabric as reinforcement material and two different types of resin materials i.e., polyethylene and polycarbonate. Three different ratios of resin and reinforcement were used to develop samples for each category. Total six samples were developed using compression molding. The flexural strength test showed that the composites with polycarbonate material E1, E2 and E3 have higher flexural strength and this strength decreases by increasing the volume percentage of resin. The tensile strength results showed that the polycarbonate resin composite E1, E2 and E3 require more force to break as compared to polyethylene/denim composites S1, S2 and S3 but side by side these samples E1, E2 and E3 have very less elongation % and high modulus as compared to the polyethylene resin composites S1, S2 and S3. The impact resistance of polycarbonate-based composite was higher than the polyethylene-based composites. These composites absorbed higher energy and required more force to break as compared to other samples. Similarly, short beam strength was higher for polycarbonate composite materials. The outcomes of this study conclude that the PIW and PCW can be effectively used to make value added products, e.g., floor tiles, packaging material, automotive interior, door panels, sandwich wall panels, etc.. The assessment of the sustainable composites from denim waste would allow comparison of their performance to the performance of traditional petroleum-based products that are harmful to the environment, which may lead to establishing a market for this new class of materials.

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