

Scrap denim-PP composites as a material for new product design

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Abstract

The growing interest of manufacturing companies to use its scraps as raw material to design and develop alternate products has led them to new ways of processing them. The present project arises from a jeans manufacturing company's interest on making an effort to reuse its daily denim scrap to manufacture a different kind of product without diversifying its capabilities. Some studies on denim-binder mixtures have been previously performed, amongst which binders such as corn starch and vinyl adhesives were used. In the present work some preliminary findings are shown using denim in its woven form combined with polypropylene, a common waste worldwide. The goal of this project is based on the assessment of some of the mechanical properties from the obtained mixtures in order to determine their attributes and possible fields of application in the process of designing new products. For that purpose, the materials' testing was structured in four stages regarding the variables linked to the diversification of the mixes. In the first stage a sandwich-like material was prepared, consisting of two denim skins and a polypropylene core. In the second stage a multilayered "film-stacking" material was developed. In the third stage, a combination was developed consisting of polypropylene mixed with 5% weight of shredded denim. Based on these preliminary findings and the inherent attributes of denim, the fourth stage is a first attempt to use the obtained materials to design new products. In this process an introductory material-product mapping was used in order to provide early insights and define scenarios and user profiles. The results of the whole process yield a first approach to configure future experiments using combinations of denim scrap and other thermoplastic polymers in order to use them in new product development.

Keywords: *Polymer-denim composites, upcycling, product development, user profiles.*

1. Introduction

There is a growing interest among some manufacturing companies to develop new composite materials based on upcycling its own industrial scrap to use it for product development. Composite materials are basically defined as a mixture of two or more constituent materials that possess different physical or chemical properties. To make such a combination, there must be at least 5% of one of these constituent elements, producing a material with considerably different properties from those of the individual components (Mathews, 2003). There are two phases in such materials: a continuous phase, known as the matrix (polymer, ceramic or metal), and a dispersed one known as the reinforcement (fibers and particles), which can have different configurations.

Polymer based composites are generally classified depending on the type of reinforcement employed in the mix: from particles of mineral origin such as talcum powder and clays, to fibers, either natural or synthetic.

In the case of polymer matrix-textile fiber mixtures, experimentation has been performed with linen using several polymer matrices such as polylactic acid (PLA), polyhydroxybutyrate (PHB), Polybutylene succinate (PBS), and polybutyrate (PBAT). It was found that the specific tensile strength and modulus of these composites were similar to those of glass fiber reinforced polyester (Bodros, et. al.: 2006) and are higher than composites such as PP-linen (Oksman, et. al.: 2003). Regarding PLA-denim composites, mechanical and thermal properties also improve compared to similar composites made with other fibers (Lee, et al: 2010). With respect to polypropylene-denim mixtures, Haque, et al (2014) reported that the more fibers are used, tensile strength decreases but in contrast, there is an increase in flexural strength.

Among industrial applications of polymer-cotton composites (denim being the most widely used) due to its properties, several car manufacturers use them in upholstered panels to improve acoustics in the interiors of certain vehicles (Ahmad, Choi & Park, 2014). Notwithstanding previous works, the present study is a first approach to evaluate such mixtures without the use of coupling or compatibility agent treatments, aiming to minimize or reduce reprocessing operations within the company.

On the other hand it is important to mention that research from Instituto Nacional de Ecología y Cambio Climático (INECC), has found that plastics constitute 11% of the total composition of waste in Mexico (Frias, Lema & Gavilán, 2007). Solid waste of thermoplastic materials can be reused as raw material to produce new products, with the caveat that these materials can degrade during thermal reprocessing, partially diminishing some of its properties compared to its virgin counterpart. Regarding polypropylene (PP), the chosen material, it is a semi-crystalline polymer (presenting both crystalline and amorphous phases) and among its most useful properties, it has a wide processing window (allowing it to be transformed using a variety of processes) presenting greater stiffness and higher melt temperature than polyethylene. This material is considered a *commodity* in the world market given the fact that its demand constitutes 25% of the world plastics production (IHS, 2015) and due its wide range of molecular architectures and grades it is used to manufacture multiple kinds of products. In Mexico, this is the highest demanded resin, reaching an estimated quota in 2012 of about 1'102,000 tons per year (Conde, 2012).

The goal of the present work is to understand the effects of denim content in a thermoplastic polymer matrix. To attain this goal, three different combinations have been studied under tensile and flexural modes. It is possible to produce composite materials with industrial scrap that have similar properties of those to the unfilled polymer matrix. This is a first approach to the subject and therefore there are several variables to be considered in order to increase the mechanical performance of the new material described

in this document. Such variables include fiber orientation (for woven textile) or the effect of temperature on the fiber during processing, just to name a few.

On the other hand, mechanical properties aside, another important aspect of this project is that unlike other fibrous materials, denim's ubiquity in the global market and acceptance among consumers from different social backgrounds and ethnical contexts, has made it an important part of modern culture for its embedded meaning (Miller & Woodward, 2007). During the design process such aesthetic and symbolic qualities were key factors to develop alternative products with the denim-PP composites.

2. Method description

2.1. Materials for stages 1, 2 and 3

For these two stages, samples were prepared using denim in its woven form. The polymer used is a PP random copolymer supplied by REPSOL (Spain) with a MFI of 21 (230 °C; 2,16 kg, ISO 1133) and a density of 0.905 g/cm³ (ISO 1183). The denim blend used has a composition of 76 % cotton warp, and 22 % polyester with 2% polyurethane weft.

For the third stage, and based on preliminary results from the previous stages, denim trim scrap was cut in small pieces and shredded using an industrial blending machine. Later the shredded denim fibers were sun dried and mixed with recycled PP scrap. This preparation used 5% wt of shredded denim fiber.

2.1.1. Sample Preparation

A compression molding IQAP-LAP model PL 15 hydraulic hot press machine was used for the sample fabrication. Two types of composite structures were prepared: a sandwich composite consisting of two denim skins and a PP core, and a multilayer laminate consisting of 4 layers of denim and 5 layers of PP in film stacking configuration. In order to obtain regular samples, the material was compression molded using a steel frame with a squared cavity of 150 mm by side and a thickness of 2.5 mm.

For the sandwich structure the core was molded with the following processing conditions: plate temperature set at 220 °C, a pressure of 4 MPa and a cooling time of 5 minutes. Afterwards the denim skins were thermally compressed to the core using the hot plates of the press during 2 minutes.

The multilayered composite was molded using an initial pressure of 1 MPa for 3 minutes to start melting the first layers of plastic and denim and pressure was progressively increased with each layer to reach 5 MPa. Temperature remained constant at 220 °C during all the forming stages.

2.1.2. Experimental procedure

Prismatic specimens for flexural and tensile testing (see figure 1) were obtained from the plaques using a precision circular saw. All tests were performed with a Galdabini Sun 2500 universal testing machine using a 5kN load cell. Three point bending flexural tests were performed in accordance to the ISO 178 standard with a crosshead speed of 1 mm/s. Tensile tests were performed in accordance to the ISO 527 standard.

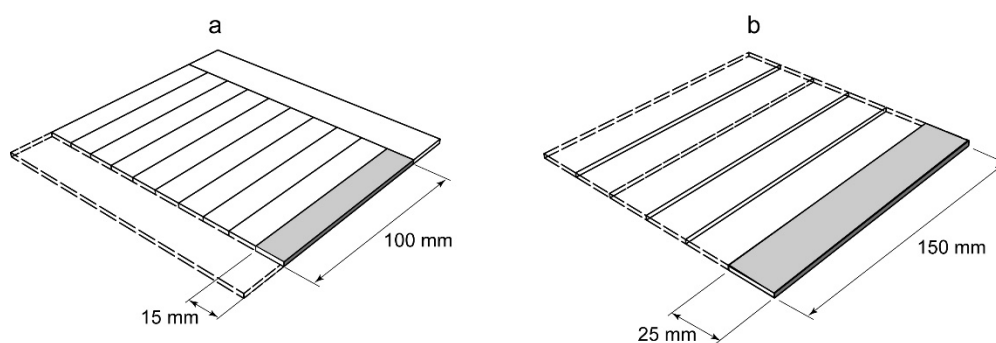


Fig. 1. Specimen sectioning for: a) flexural testing; b) tensile testing.

3. Results and discussion

Results of both, the tensile and three point bending flexural tests are presented in table 1. It can be observed that all the elastic modulus values from the new composites fall below the virgin plastic materials' and that their maximum strengths do so in a larger scale. In the specific case of the sandwich material, these values –elastic module and maximum strength- are not much different from those of the virgin polymer matrix.

The film stacking multilayered material presents even lower values to those observed on the sandwich configuration. This means that as the content of fabric increases in this composite, the mechanical properties will decline. This is attributable to the fact that the stiffness of the fabric is lower than that of the polymer matrix's, therefore instead of reinforcing the composite material it weakens the new product.

Table 1. Denim-PP composites' mechanical properties compared to virgin PP.

Specimen	Tension			Bending		
	E (MPa)	σ_M (MPa)	σ_B (%)	E_b (MPa)	σ_{M_b} (MPa)	σ_{B_b} (%)
PP (virgin)	1322 ± 78	42 ± 2	>100	737 ± 72	39,3 ± 0,3	n/b
Denim	283 ± 4	26 ± 1	30 ± 3	-	-	-
Sandwich	1064 ± 65	22 ± 3	12 ± 3	643 ± 208	19,7 ± 7,8	n/b
Film stacking	-	-	-	305 ± 70	18,5 ± 2,5	n/b
PP + denim shreds	-	-	-	551 ± 80	12,6 ± 1,0	n/b

The mechanical properties in tensile and flexural mode of these composites can be observed in figures 2 and 3. It is quite noticeable that the performance of these materials is below the performance of virgin PP. In other experiments (Foult, et al, 2006) it has been observed that the mechanical performance of the composite can increase by using coupling agents and compatibilizers.

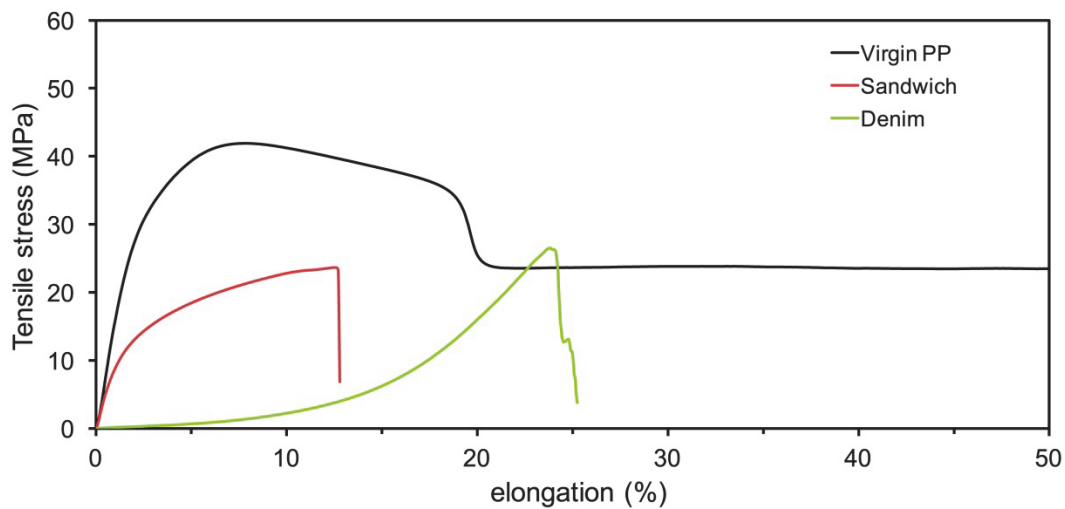


Fig. 2. Tensile behavior of denim-PP composites with respect to the unfilled material.

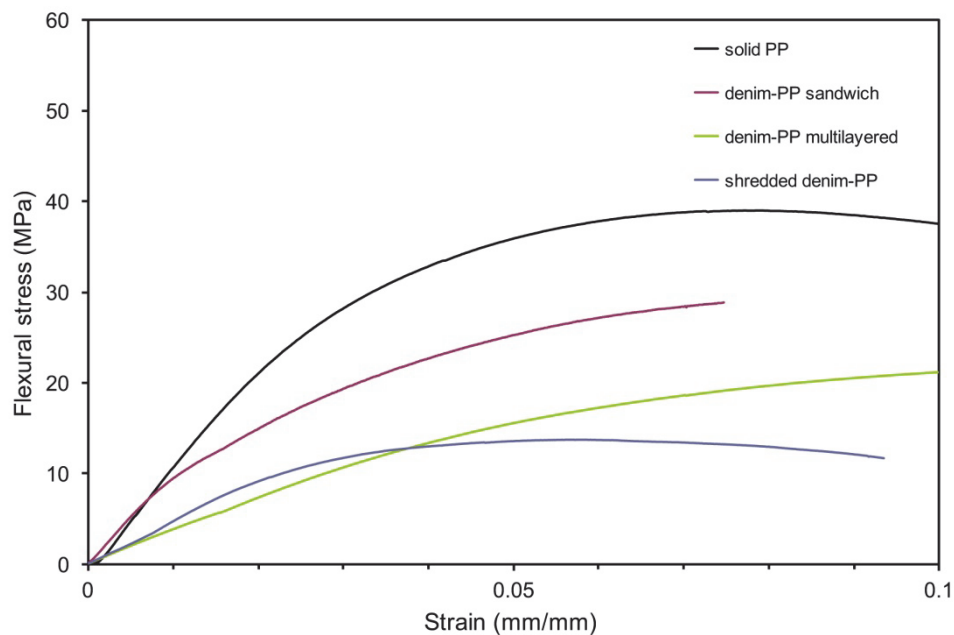


Figure 3. Comparative study of denim-PP composites' flexural behavior against virgin PP.

Considering the results from table 1, the sandwich structure in tensile mode has a Young's Modulus similar to the virgin material. This is due because at low strain rates, the fabric does not work mechanically until 10 % of elongation, whilst the denim-PP composite breaks just above this value. The maximum strength value falls down to half the one from the virgin material. Mechanically, denim fibers do not work but occupy a significant volume of the composite, therefore, denim acts more as internal and superficial defects and consequently weakens the new material. This can be seen more clearly in the ultimate strength and strain values, but not in the modulus.

Regarding flexural tests, (see figure 3) it is noticeable that they present a similar trend to the one observed in tensile mode tests. Unlike the latter, flexural tests, stop at 5% elongation, and at this point of the test the load will not break the specimen. Conversely, the material tested in tensile mode (see figure 4) displays little or no plastic deformation at the fracture zone, this means that the fabric inhibits the plastic deformation of the matrix which, by itself is capable of doing so if subjected to heavy loads. It can be observed that strain values drop significantly with the inclusion of denim fabric.

The fabric alone was tested under tensile mode and it can be observed that it tears at very long crosshead displacements (see figure 2). It is clear that this material presents very low stiffness compared to the composites but it starts tearing at higher strengths than those of the new composites.

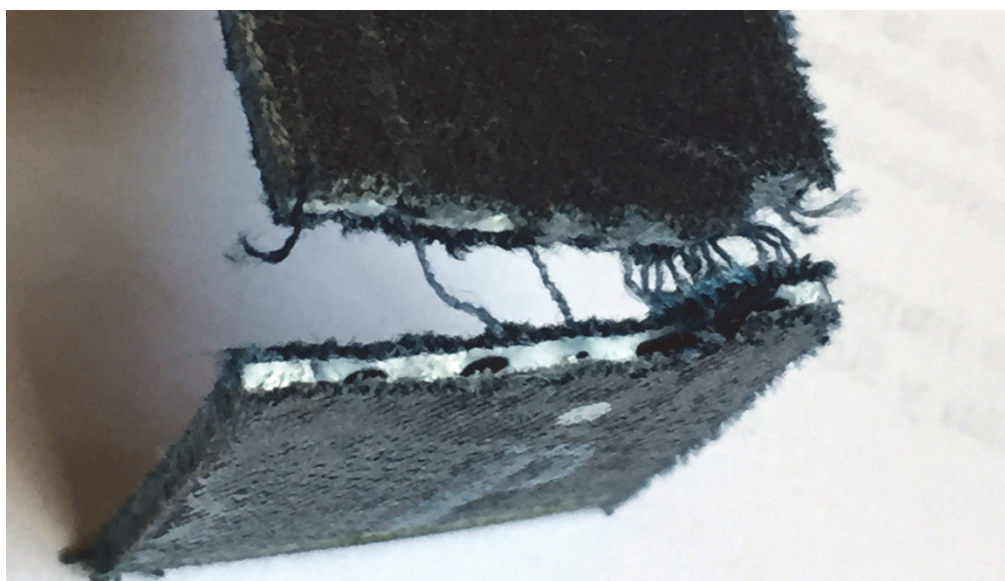


Fig. 4. Close up at the fracture zone of denim-PP tensile specimen.

Flexural tests of the shredded denim-pp mix show a similar behavior to the one observed in the sandwich and multilayered preparations. Despite displaying a lower stiffness compared to the virgin material, the values are higher than those observed in the multilayered composite. There is also a change in behavior in the elastic zone of the curve, where the slope becomes slightly steeper at low strain rates (see figure 3). This can be attributed to the presence of knots within the mix, affecting the interphase between the fibers and the polymer matrix. These samples presented low stiffness and moderate plastic deformation accompanied by delamination, hinting a possible use in applications under impact mode.

4. Stage 4: Design research and material application

Once the mechanical tests were performed, the resulting properties were given to the design teams in order to understand the material's application possibilities. Due to the fact that these composites presented similar or lower stiffness values and limited strengths compared to virgin PP, a property comparative was developed. Another important aspect that was kept in mind about the composites was its low apparent density (0.75 g/cm^3 for the shredded denim-PP composite, and 0.88 g/cm^3 for the layered materials) a quality suitable for products that could potentially benefit through weight reduction. At this point, in order

to build scenarios, the teams reviewed what had been done with denim outside the garment industry. The results of this first material-product mapping were graphically presented in material-product map shown in figure 5.



Fig. 5. Material-product mapping.

The teams identified several uses with different forms of this material: shredded fibers, partially shredded, trimmed figures, in combination with a variety of binders, such as eco-resins, and thermoplastics. In few cases, to say the least ones, some products were developed making new yarns from denim shreds to produce new fabrics.

Another key element observed during this stage was that denim fibers were visible in most of the composites developed with them, adding a distinctive trait to the final product. From this analysis, several areas of opportunity were drawn: home decoration, architectural and construction applications, car parts, fashion accessories and apparel, personalized accessories and safety gear. As research continued, the design teams observed that many of these products were offered to a particular type of user: an environmentally conscious well educated kind, yet eager to acquire new/fashionable items. Considering denim's symbolic qualities and the idea that this industrial trim/scrap can be used to make new materials and contribute to protect/preserve the environment, designers explored the possibility of developing tailor-made products.



Fig. 6. Urban cyclist psychometric profile.

For this purpose, two user profiles were studied: a) young professionals using technologies in their daily life; b) urban cyclists. In both cases, these users openly express their points of view and have an easy-going lifestyle. In the present work the attention will be given to the second group. In figure 6 the user profile is graphically explored.

Urban cyclists are a new kind of social movement. It is mostly about young people, aged between 15-25, the eldest are attending college or studying a major, and most of them are tech savvy. For this group, riding in the city is a personal statement and as they keep up with it, they are subjected to different kinds of threats, such as heavy traffic, occasional harsh weather conditions and continuous dog chases, just to name a few. The design team surveyed a sample of 100 urban cyclists from the city of Guadalajara, in order to understand their specific needs. Due to its lower stiffness, at first the team thought of designing a tool pouch based on the multilayered material, but the survey showed that most of the users would rather have someone with mechanical skills repair their bicycles. Instead, the object that was mostly sought after were cargo bags. Another question of the survey confirmed the assumption regarding the willingness to acquire products made with recycled materials: 90% had a positive response. In the following step, the team analyzed several products that were manufactured using different kinds of industrial waste, and compared their properties. A radar comparison graph is shown in figure 7.

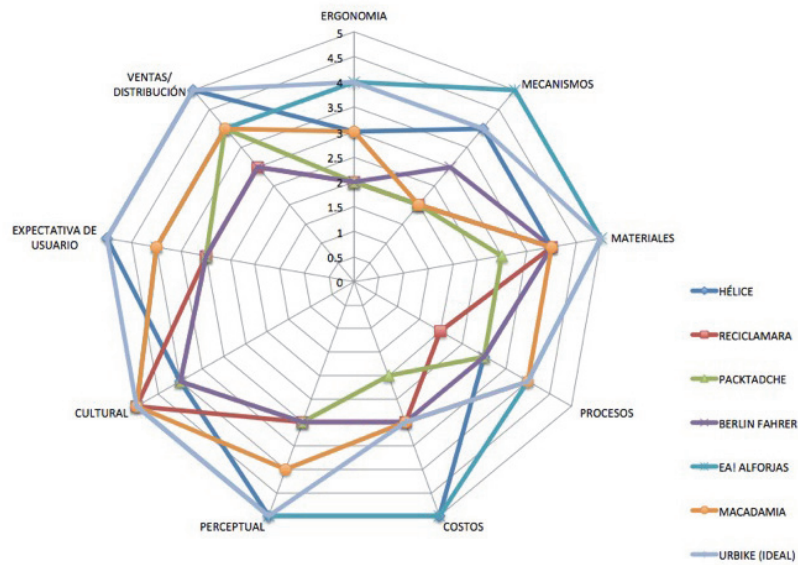


Fig. 7. Radar comparative graph.

Six products are displayed in this graph but four were rather significant by the materials employed for their fabrication: recycled tire tubes, cardboard, recovered leather, and recovered canvas. Some materials with lower densities than the denim-PP composite presented certain inconveniences: cardboard had a limited durability; tire tube products were not so appealing despite its inherent flexibility; recovered leather was relatively heavy; and canvas is not completely puncture resistant. Designers chose to use the sandwich structure instead of the multilayered, taking advantage of its higher stiffness and low density. Figure 8 shows several sketches of the product.

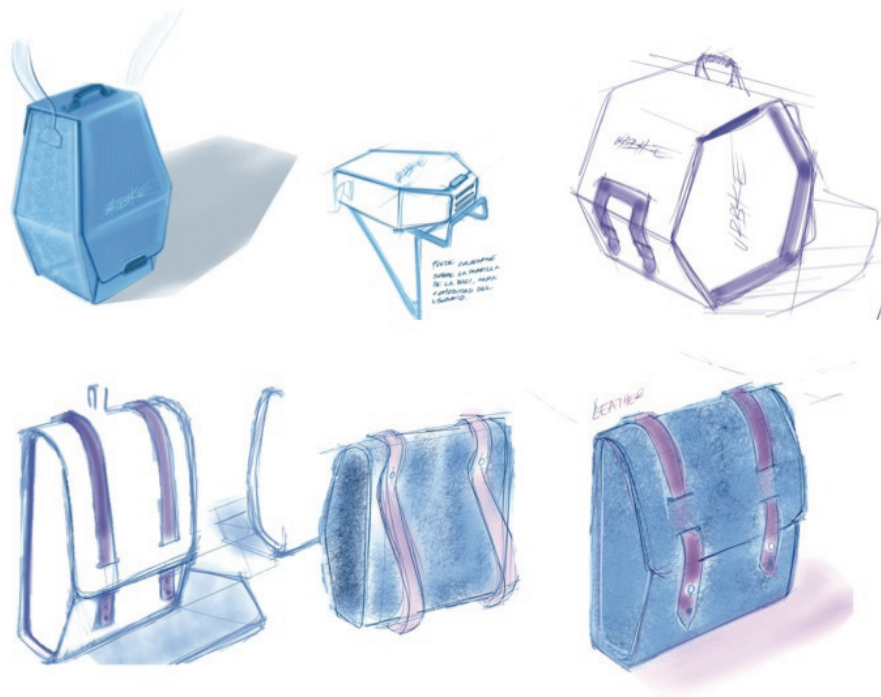


Fig. 8. cargo bag sketches.

5. Conclusions

In the present study some mechanical properties of denim scrap-PP composites were evaluated. It was observed that none of the mixtures had a higher mechanical performance than the virgin polymer matrix. Despite the results, the stiffness of some mixtures was not drastically affected by the denim fibers. Designers were able to compare the preliminary findings with data from other materials and managed to understand the possibilities of the new material to be used in the fabrication of a product. During this process, information visualization became an important strategy to understand the new materials as well as the users and their needs. It is important to note that more research is needed to fully understand the properties of the composites and assess its application for product development.

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