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Composites for Life: A Case Study

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Abstract
The usage of bio-fibres and recycled materials is a growing approach to address the ecological problems being faced today. Inspired by the guidelines defining the Waste for Life initiative, the present study reports new composite materials, based on the recycling of high-impact polystyrene, found, for instance in yogurt cups, and paper plastic laminates, deriving from disposable paper cups. Given their recycling incompatibility, paper plastic laminates are either dumped in landfills or incinerated after their first usage, threatening the environmental condition. Therefore, through the development of a new composite solution, the goal was to reduce this damaging environmental impact by providing a second life to both paper plastic laminates and high-impact polystyrene. Samples presented overall good mechanical properties, from which it is highlighted a Young's Modulus of 1.75 GPa and a Tensile Strength of 21.2 MPa, encouraging the application of the present material to identified global obstacles.

Author Keywords. Composite Materials, Recycling, Reuse, Sustainable Development, Composites Manufacturing, Project-Based Learning.

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1. Introduction

"Waste for Life" (Waste for life, n.d.) is a loosely joined network of people who are developing poverty-reducing solutions to specific ecological problems". This initiative uses scientific knowledge and technology to add value to materials seen as waste by local communities and, if possible, develop a solution to local or regional problems. *Waste for Life* hopes to connect to cooperatives and community groups that are interested in adopting simple technologies to convert waste into useful products. They are not interested in profit, but rather keen in disseminating a technology that upgrades waste plastic bags and cardboard into composite materials for domestic products, such as furniture, or in building materials such as ceiling tiles for insulation. Their twin goals are to reduce the damaging environmental impact of no recycled plastic waste products and promote self-sufficiency and economic security for populations that are at most risk (Pais 2016), by adopting a strategy based on local resources. In Figure 1, some projects developed by the *Waste for Life* network are presented.

Within the metropolitan area of Porto, Portugal, both institutions, Empresa Municipal de Ambiente do Porto (EMAP) and Serviço Intermunicipalizado de Gestão de Resíduos do Grande Porto (LIPOR), perform a fundamental role in waste treatment. After direct contact, a local characterization of the waste produced in the metropolitan area of Porto was obtained.

(a) (b)

Figure 1: Examples of applications from the WFL network: (a) Books made by recycled paper, plastics, and banana fiber; (b) Jaffna made from Rice Husk, Banana fiber and waste HDPE

The following concerns were identified:

- both polypropylene (PP), found, for instance, in rice containers, Figure 2(a), and high-impact polystyrene (HIPS), commonly used for yogurt cups, Figure 2(b), are characterized by a low second life value, meaning that the recycling of such materials is compromised and often hindered;
- natural fibres represent a big portion of the waste being produced, a category where separation is seen as unnecessary, since their recycling is mostly driven to produce fertilizer;
- single-use disposable paper cups, obtained, for instance, from paper coffee cups, as seen in Figure 2(c), represent one of the most serious problems for waste treatment in the metropolitan area of Porto, given that, currently, there are no viable recycling solutions for these types of products.

The guidelines of the present project were then drawn, intending to go further on establishing an alternative solution for the recycling of disposable paper cups, by re-utilizing the respective material combined further with reused polymers, for matrix enhancement, and fibre, for reinforcement, into forming an ecocomposite defined by relevant mechanical properties.

(a) (b) (c)

Figure 2: (a) Rice container made of PP; (b) yogurt container made of HIPS; (c) single-use disposable paper coffee cup

2. State of the Art

2.1. Ecocomposites

The term ecocomposite commonly describes a composite material with environmental advantages over traditional composites (Bogoeva-Gaceva et al. 2007). By definition, these

materials may be constituted by a natural polymer and reinforced with natural fibres (Bogoeva-Gaceva et al. 2007). Due to the increasing environmental awareness, the interest behind ecocomposites has upsurged its applications in several manufacturing areas (Thyavihalli Girijappa et al. 2019). Ecocomposites can be environment friendly, recyclable and, in some cases, developed from renewable sources. Furthermore, ecocomposites are versatile and may present similar mechanical properties to those presented by traditional composites, conveyed by the presence of natural fibres, which stand as an alternative to synthetic fibres given their wide abundance, availability, low-cost, and high specific properties (Thyavihalli Girijappa et al. 2019; Faruk et al. 2014; Bogoeva-Gaceva et al. 2007).

2.1.1. Matrices

Polymeric matrices can be composed by either thermoset or thermoplastic polymers (da Silva, Alves, and Marques 2013).

The development of thermoset composites requires the use of various other components, such as base resin, curing agents and catalysts (Saheb and Jog 1999). These materials need to be chemically cured to a highly cross-linked 3D network, which creates a tough, solvent resistant, and creep resistant structure. Thermoplastic composites, on the other hand, require less reagents, enable faster moulding, are safer to handle and possess indefinite storage life. They present great design flexibility and are easy to mould into complex parts. Based on previous works, the most commonly used thermoplastics are polyethylene (PE), polyvinyl chloride (PVC), PP and PS. For both thermosets and thermoplastics, Table 1 presents a quick recap of some critical parameters for selecting the right polymeric matrix material.

Property	Thermoset composites	Thermoplastic composites
Fibre volume	Medium to high	Low to medium
Fibre length	Continuous and discontinuous	Continuous and discontinuous
Moulding time	Slow: 0,5-4 h	Fast: less than 5 min
Moulding pressure	Low: 1-7 bar	High: greater than 14 bar
Safety/Handling	Good	Excellent
Solvent resistance	High	Low
Heat resistance	Low to high	Low to medium
Storage life	Good (6 – 24 months with no refrigeration)	Indefinite

Table 1: Properties of thermoplastic and thermoset composites

2.1.2. Fibres

Two types of fibres were considered to be used for reinforcement: synthetic fibres, in which glass fibre (GF) is highlighted; and natural fibres. GF is widely employed for composite reinforcement. Depending on its physical properties, GF can be distinguished into various different categories (Sathishkumar, Satheeshkumar, and Naveen 2014). Table 2 rounds up a range of mechanical properties to define different types of GF, explicitly type E, R and S. On the other hand, and due to the growing environmental awareness, natural fibres are attracting increasing interest for various applications (Li et al. 2020). Natural fibres are cellulose fibre reinforced materials, consisting of microfibrils in an amorphous matrix of lignin and hemicellulose in different concentrations (Saheb and Jog 1999). Beyond the ecological benefits, natural fibres present several advantages, such as high specific properties, flexibility during processing, low cost and wide abundance (Faruk et al. 2014). Table 3 presents some mechanical properties of natural fibres.

Property	E Glass	R Glass	S Glass
Young's Modulus (GPa)	73	86	85.5
Specific mass (g/cm3)	2.6	2.55	2.49
Tensile strength (MPa)	3400	4400	4580
Elongation (%)	4.4	5.2	5.3

Table 2: Properties of glass fibre

Natural Fibres	Young's modulus (Gpa)	Specific weight (g/cm^3)	Tensile strength (MPa)	Elongation (%)
Eucalyptus	17.7-21.7	0.9-1.1	116-142	1.8-2.2
Cherry Tree	10.2-12.5	0.6-0.7	88.2-108	2.3-2.9
Jute	6.0-6.5	1.4-1.6	120-145	1.5-2.5
Sisal	15-30	0.7-1.6	400-800	1.5-4.0

Table 3: Table presenting the mechanical properties of various natural fibres of interest

2.2. Paper plastic laminates

Disposable paper cups are made of a high-quality virgin cellulose fibreboard combined with a thin internal polyethylene (PE) coating (Mitchell et al. 2014), to provide impermeability and enable its usage for serving hot and cold beverages, such as coffee or tea. This material, known as paper plastic laminate (PPL), is increasingly used for many disposable products. However, given the strong bonding existing between the cellulose fibreboard and the PE coating, the separation between plastic and paper is restricted and only possible to achieve with high-end technology which common waste treatment facilities do not have access to. Therefore, the recycling of PPLs has become a major concern, with the wide majority being either disposed to landfills or incinerated (van der Harst and Potting 2013; Häkkinen and Vares 2010), defining a life cycle gathering contradictory opinions towards the respective material (Strong 2008; McKeen 2014). Given the limited recycling options for PPLs, finding alternative solutions becomes a relevant task, to which incorporating them into novel composite solutions is already being addressed by the research community (Mitchell et al. 2014).

The problem of single-use disposable paper cups has already been identified as being a worldwide concern (Ma 2018), demanding for new, more sustainable solutions. It is further suggested that education is the main driver for the change and cooperation between large companies and municipal departments is barely needed.

3. Materials and Experimental Methods

3.1. Product requirements

The present project is driven by the goal of developing a composite material, capable of relevant mechanical properties, based on the reutilization of disposable paper cups. Furthermore, it is regarded with high interest the use of other recycled, sustainable or biodegradable materials, of low second-life value, to be potentially added to the composite's matrix or as fibre reinforcement. Finally, materials are also meant to be selection based on local availability, towards promoting local resources and available waste.

3.1.1. Economic analysis

When developing a product, it is required a continuous assessment of its feasibility, by comparing the means and costs required for manufacturing, with the respective outcome associated. Therefore, to obtain a successful solution, its demand and interest must justify the resources and mechanisms required for its production. For the particular case of the present

project, such is implied by the introduction of new mechanisms to either collect disposable paper cups and other materials of interest separately, or encourage to its respective separation within waste treatment facilities. Furthermore, given the composite intends to gather materials with low value associated with their second life, the developed solution must generate enough financial interest to justify recycling the respective materials.

3.2. Identification and collection of available material and waste

3.2.1. Disposable paper cup

The recycling process of disposable paper cups represents a novel concern within the metropolitan area of Porto, enlarged by the changing of vending machines, which began providing coffee paper cups made from PPL. In the campus of the *Faculty of Engineering of Porto University* (*FEUP*), similar machines were implemented. Therefore, PPL was obtained by collecting the waste of coffee paper cups produced within FEUP's campus. After an initial contact with *FEUP*'s Sustainability Commission, it was possible to arrange a week for collection of coffee paper cups. Therefore, separate garbage bags were placed in two distinct places in the campus, for a week, towards collecting the coffee paper cups consumed by students and staff of the University. Figure 3 exemplifies the advertising and displaying of the garbage bag. It was possible to collect a significant number of cups, which, for itself, shown the considerable amount of coffee paper cups being consumed and wasted currently. It is further noted that the population at *FEUP* is estimated to be 10 000, representing a small sample of the number of inhabitants living within the metropolitan area of Porto, comprising a total of 1 722 000.

Figure 3: Separate garbage bag, on the right, for collection of disposable paper cups

3.2.2. Fibres

The present project was developed within the facilities of *Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial* (*INEGI*), which kindly provided Type E GF to be used for testing. Therefore, the designed composites solutions, which will be further introduced along the paper, were developed using GF as reinforcement. GF was prioritised over natural fibres mostly due to their respective availability, granted by *INEGI*, and ease of usage, two factors which together contributed to a faster development of product.

Nonetheless, the natural fibres considered were eucalyptus and cherry tree fibres, due their wide abundance in Porto's metropolitan area, as well as jute and sisal fibres, given their broad presence in manufacturing industries, all presenting, as well, good mechanical features.

3.2.3. Polymers

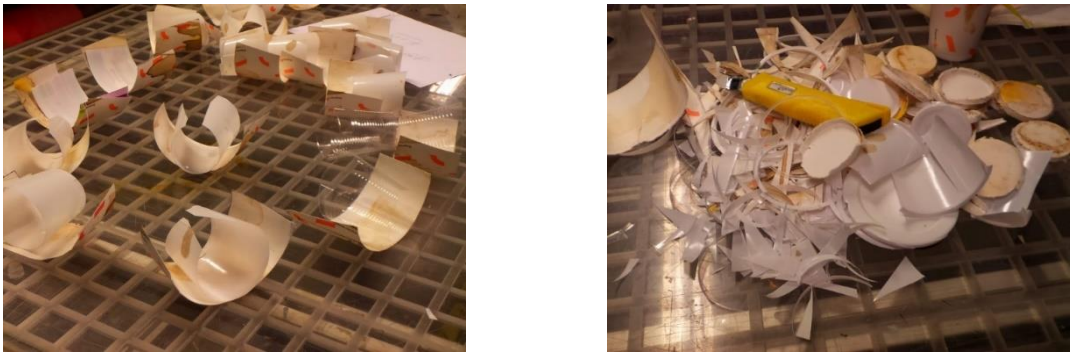
Based on its mechanical properties, but mostly due to the recycling concerns raised by both *EMAP* and *LIPOR*, the polymers selected to constitute the matrices of the composites in development, were the thermoplastics PP and HIPS. These materials were, again, locally collected as waste, by re-utilizing used rice containers, made from PP, and yogurt containers, made from HIPS.

3.3. Sample manufacturing

3.3.1. Composite design

Towards obtaining plain uniform samples, the collected disposable paper cups, yogurt and rice containers were manually cut with similar dimensions, as seen in Figure 4(a), having their format further defined with the goal of minimizing the waste produced after cutting. Therefore, a rectangular shape was adopted, with 28mm of length and 16mm of width. The samples' thickness was unique to each individual composite solution, considering that depending on the number of layers, the respective dimension would vary.

Samples were then achieved through manual labour, characterizing a procedure of high inefficiency, being both time-consuming and generating significant quantities of waste, as seen in Figure 4(b). Therefore, for high-volume production, it is recommended the implementation of a new method, which, for instance, could imply the use of a shredder to more efficiently cut all the collected waste. The composite could then be developed by depositing each layer as already described. Furthermore, it is believed that such method could provide more freedom in selecting a particular shape of interest for the composite.



(a) (b)

Figure 4: (a) different layers contemplated within the various composite samples; (b) excess material generated after sample manufacture

3.3.2. Manufacturing procedure

Given that only thermoplastics, HIPS and PP, were considered for the matrices of the designed composites, hot pressing was determined as the suitable technique to solidify and bond the layers of the various composites, by employing heat and pressure, through a mould, to enhance densification. All samples were therefore gathered and taped to a foil, as seen in Figure 5(a). Hot pressing was defined to achieve the melting temperature of the thermoplastic polymers used, thus intending to promote bonding between the layers of the composites and obtain sound structures. Table 4 summarizes all details regarding the hot pressing cycle employed. After hot pressing, only three composite solutions, through empirical analysis, shown enough layer adhesion and overall consistency to be further evaluated, as the one presented in Figure 5(b). These composites will be described in the following.

(a) (b)

Figure 5: (a) Various samples gathered in a foil before being hot pressed; (b) a sample of Composite 3 after being hot pressed

Temperature Steps	Nominal Closing Pressure [MPa]	Maximum Temperature [ºC]	Top Stage	Cool Down
Continuous heating with no steps	0.5	150	Maximum temperature held for 2 minutes	Continuous cooling with water, until reaching 45ºC

Table 4: Properties of hot pressing procedure

Characterization of selected composites

Composite 1, PPL-PPL

The first composite tested (Composite 1) was based on stacking the two layers of PPL together, following the structure: PPL-PPL. As the material is a composite already, made of cellulose fibre and a polyethylene layer, the intention was to first assess how the two layers would behave when attached together, with both PE surfaces in contact and facing each other. Therefore, the double layer of polyethylene composes, in the middle, the polymeric matrix, while in the outside, the layers of cellulose act as the fibre reinforcement. In Table 5, the layers of Composite 1 are defined in terms of volume fractions (V_f), relative to the total composite volume (V_t). Layers are displayed following the same sequence as in the composite.

Composite 2, PPL-GF-PPL

Composite 2 originated from the purpose of strengthening Composite 1 by adding one extra layer of fibre, Type E GF, in between the PE matrix, following the structure: PPL-GF-PPL. It was also intended understanding if the PE matrix would be sufficiently thick to impregnate the fibres and promote adhesion between the laminate's layers, towards enhancing its mechanical properties. Therefore, Composite 2 was developed, and it is further defined in terms of V_f through Table 5.

Composite 3, PPL-HIPS-HIPS-GF-PS-PS-PPL

One critical aspect when designing a composite material is ensuring the polymeric matrix is enough to impregnate the fibres and promote bonding between all layers. Therefore, Composite 3 was designed to enhance the polymeric matrix and guarantee a strong bonding between layers, by adding four layers of HIPS. The composite was further reinforced with GF in the middle. It follows the structure: PPL-HIPS-HIPS-GF-HIPS-HIPS-PPL. Composite 3 is seen in Figure 5(b) after hot pressing, and is further defined in terms of Vf in Table 5.

Untested prototypes

Various other composite solutions were designed by changing the number of layers, the materials present in the matrix, and the composite's overall structure. However, and mainly due to lack of bonding between layers, most of the prototypes were not consistent nor solid enough to be considered for further analysis. Some possible causes for the lack of bonding between layers are humidity or the fact that the melting temperature might not have been properly reached in some cases.

Composite 1, PPL-PPL							
Material **V_f**	Cellulose (1/4)		PE (1/2)		Cellulose (1/4)		
Composite 2, PPL-GF-PPL							
Material **V_f**	Cellulose (1/5)	PE (1/5)	GF (1/5)	PE (1/5)	Cellulose (1/5)		
Composite 3, PPL-HIPS-HIPS-GF-HIPS-HIPS-PPL							
Material **V_f**	Cellulose (1/9)	PE (1/9)	HIPS (1/9)	GF (1/9)	HIPS (1/9)	PE (1/9)	Cellulose (1/9)

Table 5: Distribution of layers per fractions of volume in the selected composites

3.4. Tensile testing

To provide a mechanical characterization of the composites obtained, these progressed for evaluation through tensile testing. It was adopted the standard *ISO 527 – Part 3*, which further required samples to be standardized and the procedure to meet specific criteria, as it will described in the following.

3.4.1.Sample standardization

To proceed with tensile testing, according to the standard *ISO 527 – Part 3*, samples required to undergo a process of standardization, which determined dimensions to be equal to 150 mm, in length, and 20mm, in width. Therefore, samples were recut to meet the standard criteria, acquiring the shape presented in Figure 6. Thickness of samples was dependant on the number of layers each composite presented and, therefore, varied between composites. The dimensions obtained for each sample are displayed in Table 6. Given the limited availability to perform tensile testing, only a restricted number of samples undergone the evaluation. Therefore, priority was conceded to Composite 3, due to its more robust structure, enabling 5 samples to be tested, while Composite 2 and 1 were secondary and restricted to 2 samples each.

Figure 6: Some standardized samples

Composite	Sample number	Thickness, h (mm)	Width, b (mm)	Length, L (mm)
PPL-PPL [1]	1	0.55	19.35	150
	2	0.55	20.7	150
PPL-GF-PPL [2]	1	0.9	19.1	150
	2	0.9	18.8	150
PPL-HIPS-HIPS-GF-HIPS-HIPS-PPL [3]	1	1.75	20.4	150
	2	1.25	20.25	150
	3	1.25	20.4	150
	4	1.6	20.5	150
	5	1.4	20	150

Table 6: Dimensions of tested samples

3.4.2. Equipment and procedures for tensile testing

Tensile testing was performed by using equipment from the global supplier *MTS Systems Corporation* (Eden Prairie, Minnesota, USA), specifically the load cell model 661 1SF-22, with capacity of 10 KN, and the strain gauge model 632 12C-20, with displacement of 0.25 mm.

Samples were fixed to grips through clamping. The free surface distance of samples was determined equal to 80mm. The strain gauge was placed in the middle of the sample's free surface and fixed by elastic clamping. Tensile testing consisted of applying an incremental loading at a constant speed of 1 mm/minute until rupture.

3.4.3. Mechanical parameters

Tensile testing was performed until rupture, partial or total. It occurred in various locations throughout the sample's length. Data was post-processed using MATLAB® software, to characterize the elastic behaviour of the samples. The applied load was first converted into applied stress by taking into consideration each sample's cross-section area. Through the post-processing of data, it was possible to characterize each sample via stress-strain graphs and by providing values for the Young's modulus, tensile strength, elongation and toughness. The Young's modulus was obtained by following the instructions detailed in the ISO 527 – Part 3 standard, therefore, performing the following calculation:

$$\varepsilon i = 0.05\% \Rightarrow \sigma i(0.05) \; and \; \varepsilon f = 0.25\% \Rightarrow \sigma f(0.25) \quad (1)$$

$$E = (\sigma f - \sigma i)/(\varepsilon f - \varepsilon i) = (\sigma(0.25) - \sigma(0.05))/(0{,}25 - 0{,}05) \quad (2)$$

Tensile strength was obtained by determining the highest recorded value during the tensile testing of each sample. Elongation, on the other hand, was calculated as the percentage of plastic strain endured by the sample before rupture. The highest recorded value for applied tension was considered as the rupture point. Toughness was further determined by calculating the area underneath the stress-strain curve. To do so, it was necessary to establish a sum of every individual area corresponding to the interval between measuring point i and N. The method can be described as follows:

$$\sum_{i=1}^{N} ((\sigma i + 1 + \sigma i)(\varepsilon i + 1 - \varepsilon i))/2 \quad (3)$$

Where N is the number of measure points for each tensile testing. All these routines were implemented as individual functions in MATLAB®, to allow for an individual analysis of every sample and respective properties.

Furthermore, software CES EduPack® was used to catalogue each composite obtained and their individual mechanical features, allowing for a posterior comparison between the properties of current composite materials and the ones presently developed.

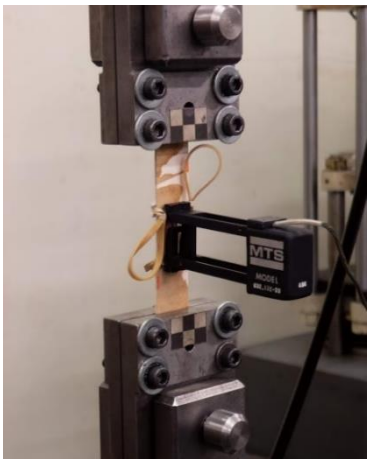


Figure 7: Settings for tensile testing

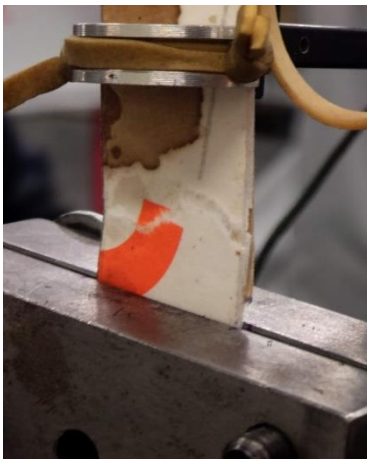


Figure 8: Rupture along the sample after testing

4. Results and Discussion

Results from tensile testing were translated into stress-strain curves, to provide mechanical characterization for each sample and composite. Results are presented in Figure 9, gathered within the same graph and overlapped for comparison. Distinction between composites is established as follows: the blue lines represent the mechanical profiles of each sample tested from Composite 1; the red lines, similarly, represent the samples tested from Composite 2; finally, the green lines represent the five samples tested from Composite 3.

Results are clear to indicate Composite 3 as presenting the best elastic properties, characterized by a higher Young's modulus, as illustrated by the steep slope of the stress-strain curve. It follows Composite 2 and only then, Composite 1, displaying a poorer elastic behaviour defined by a lower Young's modulus. However, Composite 1 was shown to possess better tensile strength than Composite 2, which presents the lowest values for this parameter. Composite 3 displays, again, the highest values for tensile strength. Regarding plastic behaviour, Composite 1 performs better, as it presents a greater capacity for plastic deformation before rupture, while on the other hand, both Composite 2 and 3 are shown to be very brittle. It should be further noted the unusual behaviour of Composite 2, whose stress-strain curve peaks twice, likely evidencing the lack of bonding between the layers of GF and PE, resulting from a thin polymeric matrix incapable of fully impregnating fibres. Therefore, the first peak was understood to represent the rupture of the PPL, while in the second it was the GF. Overall, steadier results were demonstrated by Composite 1, as visible in Figure 9,

which, given its simpler composition, enabled for better reproducibility. On the other hand, both Composite 2 and 3 present a significant discrepancy between the mechanical performances displayed by each sample. This inconsistency is justified by the frailty of the performed manufacturing method, which, due to a higher structural complexity, was unable to ensure enough reproducibility. Table 7 summarizes the results that will be further discussed in the following sections, subdivided into each mechanical parameter.

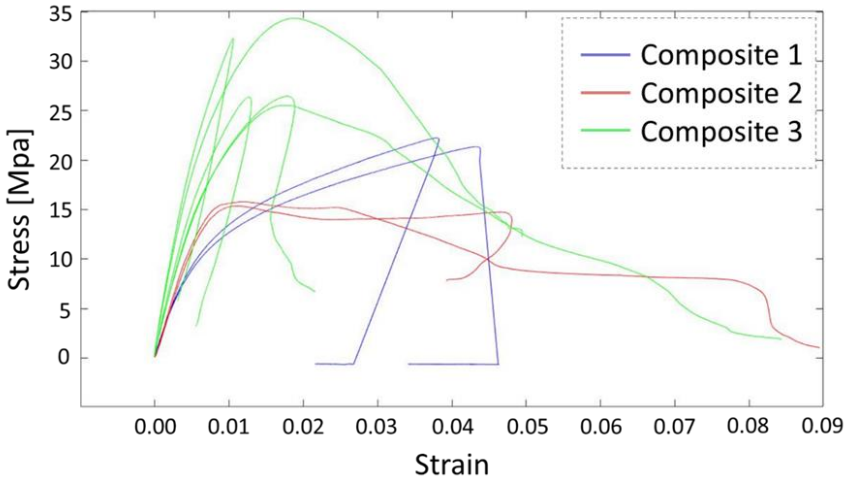


Figure 9: Stress-strain curves of each tested sample overlapped, where samples from Composite 1 are in blue, from Composite 2 in red, and from Composite 3, in green

Composite	Sample	Young's Modulus (GPa)	Tensile strength (MPa)	Elongation (%)	Toughness (kJm^2)
1	Average	2.02	21.81	2.98	0.64
	Standard Deviation	0.01	0.63	0.40	0.04
2	Average	2.48	15.59	0.53	0.13
	Standard Deviation	0.10	0.30	0.03	0.01
3	Average	3.43	28.99	0.69	0.30
	Standard Deviation	0.59	4.02	0.31	0.10

Table 7: Values for the mechanical parameters of each composite

4.1. Young's modulus

Composite 3 presented the higher values for Young's modulus, averaging 3.43 GPa, followed by Composite 2, with 2.48 GPa, and only then Composite1, with 2.02 GPa. The superior performances of both Composites 2 and 3 were considered to result from the presence of GF as reinforcement, which stiffened the composites and provided better elastic properties. Nonetheless, a significant gap still exists between the two Composites, which is believed to be due the presence of different matrices in each composite. While for Composite 2, only two layers of the thin PE coating from the PPL comprise the matrix, to Composite 3 four more layers of HIPS are added to reinforce its polymeric matrix. Such determines better adhesion properties to be established between the fibres and the matrix, ultimately resulting in greater elastic capabilities, and defining Composite 3 as the most solid and reliable structure.

By using CES EduPack® to catalogue each composite's tensile strength, Figure 10 was obtained to illustrate how the respective composites perform when compared to the realm of current composite materials.

4.2. Tensile strength

Regarding tensile strength, whereas Composite 3 presents, again, the highest recorded values, with an average of 28.99 MPa, Composite 1 outperforms Composite 2, by displaying greater tensile strength, determined with an average of 21.81 MPa, hence superior to the values obtained for Composite 2, which only reached 15.59 MPa in average. While the better performance of Composite 3 is again justified by the presence of GF as reinforcement, which further benefits from a well-established bonding between fibres and matrix, Composite 2 falls short on this last particular property. Even though GF was implemented to enhance mechanical properties, the polymeric matrix was not capable of fully impregnating the fibres, resulting in lack of bonding between layers and ultimately, in this case, a poor tensile strength. On the other hand, however, Composite 1 presented high values for tensile strength, reflecting the fine structural consistency obtained between layers. It is finally noted that the analysis of tensile strength should be done considering the increase in section area resulting from the addition of layers, such as with GF and HIPS, as previously demonstrated through Table 6.

CES EduPack® was used, again, to list the properties obtained for each composite and allow for a comparison between the developed solutions and the rest of the composite universe, regarding tensile strength, as seen in Figure 10.

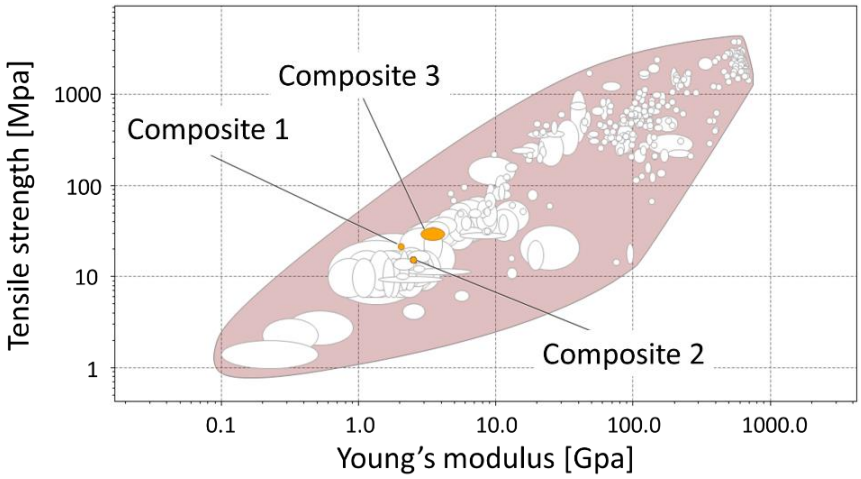


Figure 10: Realm of composite materials and respective range for Young's modulus and tensile strength, with the developed composites in orange

4.3. Elongation

Composite 1 presented the better elastic properties, with a superior capacity for elongation, reaching 2.98% in average. Presenting much lower performances, Composite 2 and 3 demonstrated, on the other hand, a clear inaptitude for plastic deformation, defined by values for elongation with an average of 0.53% and 0.69% respectively. Even though implementing GF as reinforcement may enhance the stiffness properties of composites, as demonstrated previously for Composite 3, it can also backfire within the realm of plastic deformation, by defining materials to be more brittle. Therefore, whereas Composite 2 and 3 present a lower aptitude for plastic deformation before rupture, being classified as the most brittle, Composite 1 exhibits a superior performance, characterized by a better capacity for elongation, hence being the most ductile.

Values for elongation were further catalogued within the database of CES EduPack® to, once again, place the obtained solutions within the realm of composites, as it is visible in Figure 11.

4.4. Toughness

Toughness, being defined as the area below the stress-strain curve, as indicated by Equation 3, is directly influenced by all the previous features. Composite 1 shows better toughness, presenting an average of 0.64 kJm^2, followed by Composite 3, with an average of 0.30 kJm^2, and only then Composite 2, displaying the lowest toughness values, with an average of 0.12 kJm^2. This characterization means that Composite 1 is able to absorb more energy before rupture. The absence of GF allowed Composite 1 to present better plastic capabilities, while compensating for the lower tensile strength, ultimately resulting in a tougher material. On the other hand, Composite 2 and 3 are hindered by their brittle behaviour, which leads to a lower toughness. More so, Composite 2 is further affected by the poor bonding established between layers, which ultimately defines the composite to be the least tough.

Toughness was also recorded within CES EduPack®, to therefore compare the properties of the developed solutions with the ones presented by existing composites, as it is shown in Figure 11.

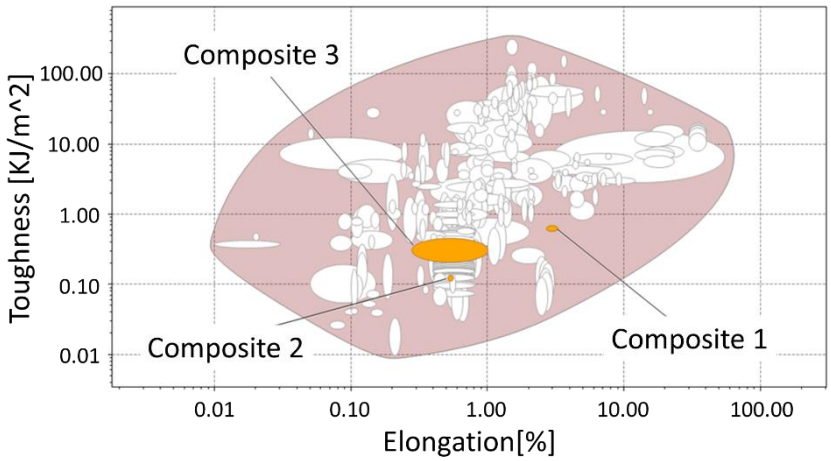


Figure 11: Realm of composite materials and respective range for elongation and toughness, with the developed composites in orange

5. Conclusions

Following the main guidelines of the initiative *Waste for Life*, an approach was established and accomplished for developing new composite materials, based on local available waste, and focused on solving a locally identified problem with, however, a worldwide impact.

By establishing contact with both EMAP and LIPOR, institutions which deal with waste treatment within the metropolitan area of Porto, Portugal, it was possible to identify disposable paper cups, made from paper plastic laminate (PPL), as representing a critical and current problem for recycling. Furthermore, the recycling of polymers such as polypropylene (PP) and high-impact polystyrene (HIPS), was also regarded as a concern, given that it is currently compromised by their low second life value. Therefore, composites were developed, based on reutilizing the respective materials and by adding Type E Glass Fibre (GF) as reinforcement. Three composites were further selected, with compositions based on the simple stacking of two PPL layers - Composite 1 – further reinforcement with GF – Composite 2 – and final enhancement of the polymeric matrix with HIPS – Composite 3. These composites were subjected to tensile testing, through which it was possible to characterize their mechanical behaviour, by obtaining each respective stress-strain curve and gathering data for Young's modulus, tensile strength, elongation and toughness. It is highlighted the better elastic properties of Composite 3, with a Young's modulus of 3.43 GPa, and greater tensile

strength, of 28.99 MPa. On the other hand, Composite 1 is likewise highlighted, due to its superior ductility, capable of 2.98% of elongation, and higher toughness, of 0.64 KJ/m^2. Composite 2 shown the least favourable properties, which was understood to be resultant from the lack of bonding established between its polymeric matrix and the fibres.

For future works, it would be of interest proceeding with tensile testing to a much larger amount of samples, towards characterizing with higher precision and improved accuracy the composites developed by the present work. Furthermore, it would be relevant characterizing the composites to a wider range of properties, which could imply both creep and humidity testing. Substituting the GF for a natural fibre with local relevance, such as eucalyptus, cherry tree, jute or sisal, would be of great interest for the project as well, towards fully accomplishing the definition of an ecocomposite. Finally, employing a new method for manufacturing, which could imply the use of a shredder to cut all materials, would be extremely valuable to ensure better reproducibility of samples.

5.1. Application of interest

Towards generating interest for recycling of the materials here involved and respective reutilization, by forming composites the way described, it is suggested a practical application, which was identified as being relevant for the developed composites.

The shipping and transport of books, and other goods, is currently compromised by the boxes in which they are carried, commonly made from corrugated cardboard. This material not only lacks on impermeability, but also possesses low mechanical properties, which together result in books commonly arriving wet or damaged. This problem was identified in 2019 by Diamond Comics (Diamond Comic Distributors, n.d.; Bleeding Cool 2019), characterizing a concern of a wide scale. The work of Aboura et al. (2004) provides mechanical characterization for corrugated cardboard, attributing a Young's modulus of 0.9 GPa and a Tensile Strength of 4.5 MPa.

All composites tested shown better mechanical properties than the ones presented by corrugated cardboard, suggesting that the composites developed by the present project could represent a suitable material, as an alternative for the development of shipping boxes and a solution to the identified problem. Not only due to its mechanical properties, but also given its innate impermeability, conveyed at least, in all composites, by the PPL layer.

References

Aboura, Z., N. Talbi, S. Allaoui, and M. L. Benzeggagh. 2004. "Elastic behavior of corrugated cardboard: Experiments and modeling". *Composite Structures* 63, no. 1: 53-62. https://doi.org/10.1016/S0263-8223(03)00131-4.

Bleeding Cool. 2019. "Dennis Barger on Diamond Comic Distributors' new boxes". https://bleedingcool.com/comics/dennis-barger-diamond-comic-distributors-new-boxes/.

Bogoeva-Gaceva, G., M. Avella, M. Malinconico, A. Buzarovska, A. Grozdanov, G. Gentile, and M. E. Errico. 2007. "Natural fiber eco-composites". *Polymer Composites* 28, no. 1: 98-107. https://doi.org/10.1002/pc.20270.

da Silva, L. F. M., F. Alves, and A. Marques. 2013. *Materiais de construção*. Publindústria.

Diamond Comic Distributors. n.d. "Diamond begins using new, stronger shipping box for retailer orders". Accessed November 25, 2019. https://www.diamondcomics.com/Home/1/1/3/597?articleID=238063.

Faruk, O., A. K. Bledzki, H. P. Fink, and M. Sain. 2014. "Progress report on natural fiber reinforced composites". *Macromolecular Materials and Engineering* 299, no. 1: 9-26. https://doi.org/10.1002/mame.201300008.

Häkkinen, T., and S. Vares. 2010. "Environmental impacts of disposable cups with special focus on the effect of material choices and end of life". *Journal of Cleaner Production* 18, no. 14: 1458-63. https://doi.org/10.1016/j.jclepro.2010.05.005.

Li, M., Y. Pu, V. M. Thomas, C. G. Yoo, S. Ozcan, Y. L. Deng, K. Nelson, and A. J. Ragauskas. 2020. "Recent advancements of plant-based natural fiber-reinforced composites and their applications". *Composites Part B-Engineering* 200 (november): 108254. https://doi.org/10.1016/j.compositesb.2020.108254.

Ma, Y. H. 2018. "Problems and resolutions in dealing with waste disposable paper cups". *Science Progress* 101, no. 1: 1-7. https://doi.org/10.3184/003685017x15129981721365.

McKeen, L. W. 2014. "Plastics used in medical devices". In *Handbook of polymer applications in medicine and medical devices*, 21-53. Elsevier. https://doi.org/10.1016/B978-0-323-22805-3.00003-7.

Mitchell, J., L. Vandeperre, R. Dvorak, E. Kosior, K. Tarverdi, and C. Cheeseman. 2014. "Recycling disposable cups into paper plastic composites". *Waste Management* 34, no. 11: 2113-19. https://doi.org/10.1016/j.wasman.2014.05.020.

Pais, D. F. L. 2016. "Conceptual design and characterization of composite systems for housing". Master's thesis, Faculty of Engineering, University of Porto, Portugal. https://repositorio-aberto.up.pt/handle/10216/85928.

Saheb, D. N., and J. P. Jog. 1999. "Natural fiber polymer composites: A review". *Advances in Polymer Technology* 18, no. 4: 351-63. https://doi.org/10.1002/(Sici)1098-2329(199924)18:4<351::Aid-Adv6>3.0.Co;2-X.

Sathishkumar, T. P., S. Satheeshkumar, and J. Naveen. 2014. "Glass fiber-reinforced polymer composites - a review". *Journal of Reinforced Plastics and Composites* 33, no. 13: 1258-75. https://doi.org/10.1177/0731684414530790.

Strong, A. B. 2008. *Fundamentals of composites manufacturing: Materials, methods and applications*. Society of Manufacturing Engineers.

Thyavihalli Girijappa, Y. G., S. Mavinkere Rangappa, J. Parameswaranpillai, and S. Siengchin. 2019. "Natural fibers as sustainable and renewable resource for development of eco-friendly composites: A comprehensive review". *Frontiers in Materials* 6: 226. https://doi.org/10.3389/fmats.2019.00226.

van der Harst, E., and J. Potting. 2013. "A critical comparison of ten disposable cup LCAs". *Environmental Impact Assessment Review* 43: 86-96. https://doi.org/10.1016/j.eiar.2013.06.006.

"Waste for life". n.d. Accessed September 23, 2019. www.wasteforlife.org.

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