Composites Meet Sustainability – Proceedings of the 20th European Conference on Composite Materials, ECCM20. 26-30 June, 2022, Lausanne, Switzerland

MANUFACTURING AND MECHANICAL CHARACTERISATION OF UNIDIRECTIONAL FIQUE FIBRES REINFORCED POLYPROPYLENE COMPOSITES

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Abstract: *New sustainable composites have gained considerable attention in recent years and implementing natural fibres as reinforcement in composites is growing faster in engineering applications. This work presents the development, processing, and characterisation of a new composite material by combining textile polypropylene (PP) and long Fique fibres (a South American Andes native fibre). The samples are made out using coated Fique fibres and compared with samples of only PP. The consolidation is carried out using hot pressing at 185°C and a pressure of 10MPa. Tensile, bending, Charpy and DSC tests are conducted to evaluate the thermo-mechanical properties of the new material. The PP-Fique composite with coated fique fibres shows a remarkable increment in the mechanical properties in comparison with PP. Implementing Fique fibres as reinforcement in PP will reduce the amount of plastic required keeping mechanical performance.*

Keywords: Fique Fibres; Hot Pressing; textile polypropylene; Composites; thermo-mechanical properties

1. Introduction

Agro-based structural materials are growing in different industrial applications and natural fibres are gaining attention due to their low cost, low density, minimal health hazards, biodegradability and specific mechanical properties [1-3]. Natural fibres are widely used in geotextiles, sorbents, filters, structural and non-structural parts and among others. Being implemented in industries such as packaging, building, furniture, sport and automotive [4,5]. The use of natural fibres in composites materials is growing by 6% annually, being wood fibres the most used followed by more sustainable fibres such as jute, sisal, kenaf and hemp [6,7]. Natural fibres can even replace some synthetic fibres, having distinct advantages over glass fibre in application with low loading requirements. Natural fibres have comparable strength to glass fibre and a similar specific modulus [8,9]. As an example, Flax fibres have a tensile strength of 600 to 2000 MPa and Young's modulus ranging between 12 to 100 GPa, being comparative with E-glass and having 40% lower density [10].

Fique Fibres are relatively unknown natural fibres native to the South American Andes and obtained from the leaves of the fique plant. Fique fibres are mainly made of cellulose, hemicellulose and lignin with average contents of 52.3, 23.8 and 23.9% respectively [11]. Colombia produces approximately 30.000 tons of fique fibres per year and despite Fique fibres showing good mechanical properties for engineering application, the use of Fique fibres as a reinforcement of composite materials has not been widely investigated [12-14]. Fique fibres are mainly found in the Colombian market as ropes, cordages, textiles and sackcloth for agricultural products such as coffee sacks and the cost of processed fique fibres vary between US$0.36 to US$0.45 per kg [15].

On the other hand, plastic is widely applied across all areas, and it represents one of the most important elements of modern life. More than 300 million tons of plastic materials are produced every year with most discarded-on land fills, in the ocean or incinerated [16,17]. Polypropylene is the second plastic more used after polyethene and represents 20% of the market and continues to grow [18]. Polypropylene is a thermoplastic, with good stiffness, low density, chemical resistance and low cost and it is used in different applications such as automobile bumpers, boat hulls, household goods, containers and among others [19-21].

Plastic waste causes global environmental and health problems such as pollution and loss of biodiversity. This project proposes a new composite material using polypropylene fabric and natural Fique fibres as reinforcement. The use of Fique fibres allows an increment in the flexural, tensile and impact properties of the polypropylene, reducing the cross-section area and therefore the amount of material needed in certain applications.

2. Materials

Fique fibres and polypropylene fabric are provided by the Colombian company Compañia de Empaques. The fibres are obtained from the leave of the Fique plants through mechanical decortication, cleaned in water at room temperature for 12 to 15 hours and dried naturally by the sun. During the production process, a vegetal oil is sprinkled to reduce friction and the fibres are aligned to obtain a continuo yarn. On the other hand, PP corresponds to a plain homopolymer PP fabric. The PP yarns are flat tape of PP with a width of 2.5mm and a thickness of 41µm manufactured in a drawing process. Table 1 shows some properties of the Fique fibres and PP tapes in tension.

Table 1: Summary of the mechanical properties.

Property	Fique Fibres	PP Tapes
Young modulus [GPa]	9.3 GPa (SD: 3.2GPa) [a]	6.7 GPa (SD: 0.3 GPa) [b]
Tensile strength [MPa]	340 MPa (SD: 106) [a]	382 MPa (SD: 6MPa) [b]
Elongation at break [%]	3.8% (SD: 1.5) [a]	24.9 (SD: 2.0) [b]

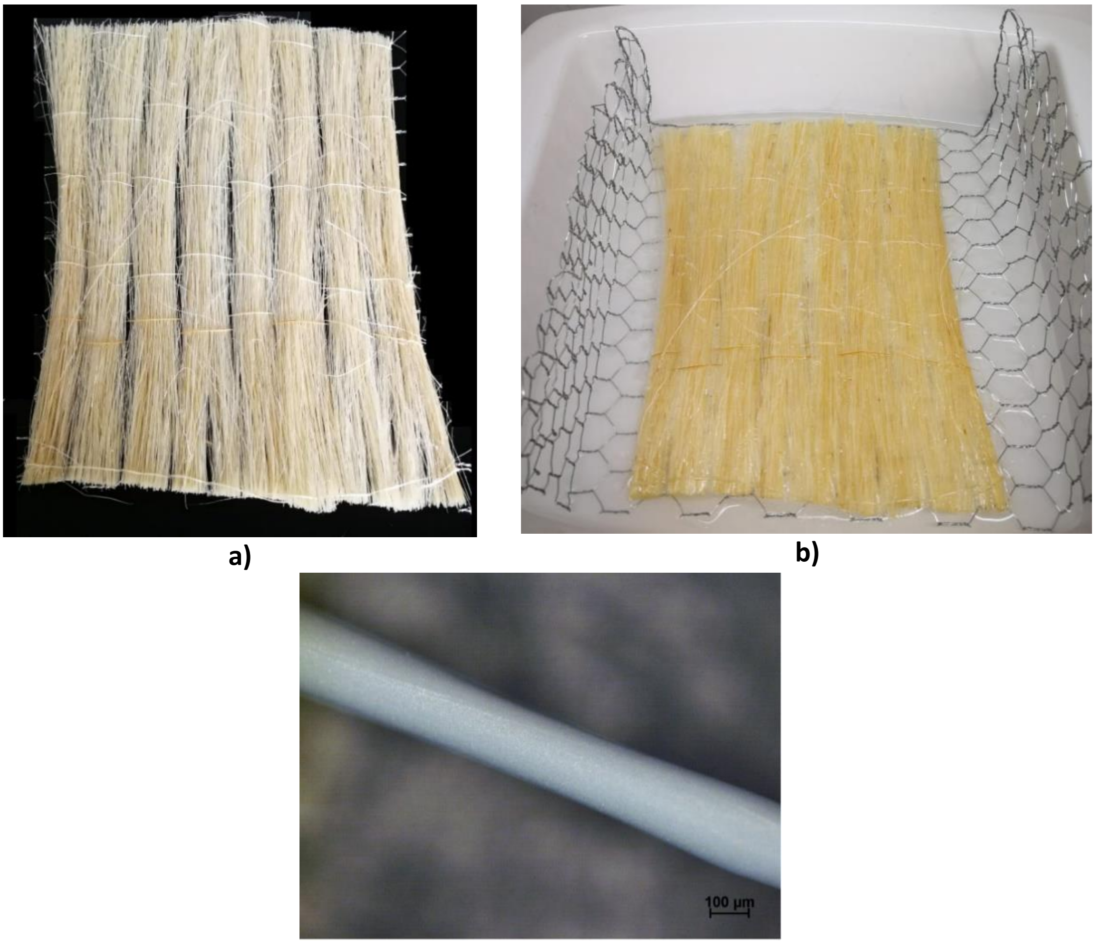
[a] Average value taken from [22]

[b] Measured during this work

3. Composite manufacturing

3.1 Fique laminates and coating process

To produce the unidirectional laminates of Fique, the continuo yarn is manually combed to remove impurities and reduce waviness. Groups of yarns are placed next to each other and tied using a fique fibre as a warp, unidirectional fique laminates are obtained as Figure 1a shown. For the coating, virgin pellets of the homopolymer PP are used, the pellets are diluted in Xilol in a proportion of 20ml of Xilol per 1g of PP. The pellets of PP and the Xilol are mixed at 120°C for 25 minutes, time enough to make the PP diluted completely. Then, the unidirectional Fique laminates are introduced in the bath for 10 minutes as Figure 1b shows. Microscopy images of the Fique fibre after coating indicate that the fibres are completely coated by the PP showing that the coating process is implemented properly, see Figure 1c.



a) **b)**

c)

Figure 1. a) Unidirectional laminates, b) coating process, c) microscopy image of a fibre coated with PP.

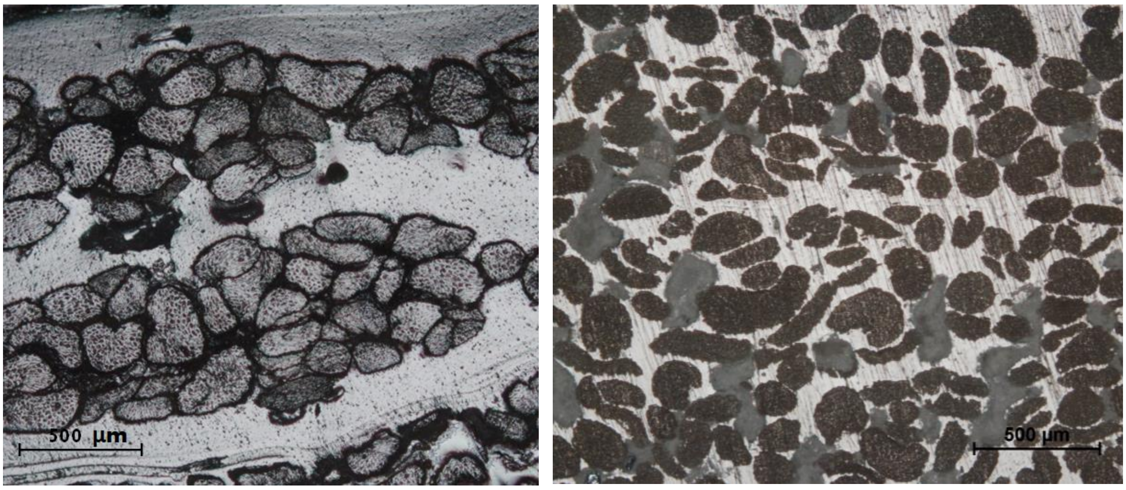
3.2 Processing temperature

To determine the temperature of the consolidation process using hot pressing, a differential scanning calorimetry (DSC) test is carried out on the Fique fibres and the PP. According to the DSC, two exothermic reactions are identified. The first reaction is produced by the degradation of hemicellulose, starting at 260°C with a peak at 295°C and the second reaction is produced by the degradation of the cellulose, starting at 360°C with a peak at 390°C. Because lignin is a complex polymer it has a wide range of thermal degradation temperatures (115°C - 500°C) [22,23]. The DSC results of PP show an endothermic reaction at 165°C which corresponds to melting point. Considering that the processing temperature should be enough to melt the PP but not too high to degrade the Fique fibres, 185°C is set as the processing temperature.

3.3 Hot pressing

The consolidation of composites is conducted in a Wickert hot pressing machine. For the process, rectangular steel moulds are used, the layers are introduced in the mould at room temperature (~25°C) and compressed to reach 10MPa. The layers are heated up to 185°C at a rate of 10°C per minute and kept at that temperature for 15 minutes. Then the layers are cooled down using a water-cooling system until a temperature of 90°C. At this temperature, the pressure is released and finally, the material is removed from the mould at 60°C.

Preliminary consolidations show that uncoating fibres generate clusters with poor penetration of the PP inside of the fibres while coated laminates show a better distribution of fibres in the composite. Figure 2 shows micrographs of uncoating and coating Fique fibres used as reinforcement in the PP laminate.



a) b)

Figure 2. microscopy image of a laminate with a) uncoated fibres b) coated fibres.

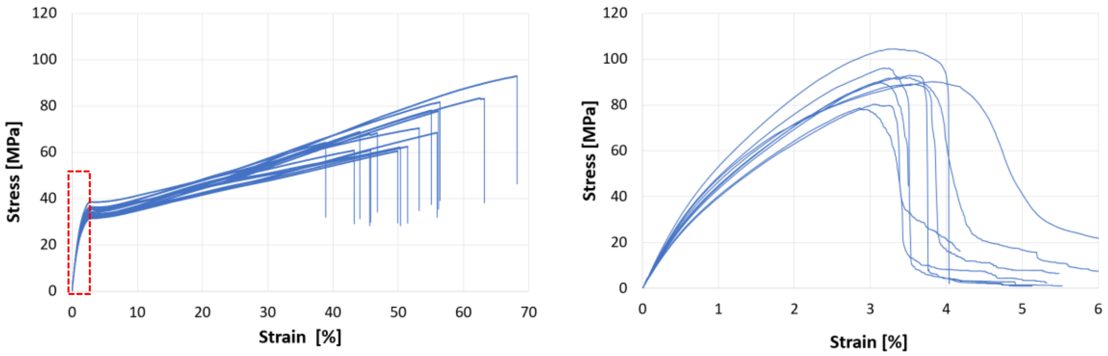
4. Tests and results

4.1 Fique Fibres Tensile tests

For the tensile tests, the samples are manufactured according to the method described in section 3.3. A rectangular mould is used with dimensions of 160x140x3mm, height, width and thickness respectively. The stacking sequence for PP-Fique laminates is [PP_2/Fique/PP/Fique/PP/Fique /PP_2], while for the laminates of only PP, 35 layers are used to keep similar thickness, [PP_{35}]. After hot-pressing, the samples are cut using a laser cutting machine, obtaining dog-bone samples with a test length of 45 mm (SD:1.0mm), test width of 12.7mm (SD:0.1mm) and a thickness of 3.0 mm (SD: 0.1mm), see Figure 3.

Figure 3. Samples for tensile tests PP reinforced with coated Fique fibres

The tensile tests are conducted in a computer-controlled Instron 3382 universal servo-electric test machine with a displacement control crosshead speed of 2 mm/min. Figure 4a shows the results of only PP samples. The first part of the stress-strain curves (red rectangle in Figure 4a) has high stiffness with a Young modulus of 2.8 GPa (DS: 0.1GPa). After 3.2% (DS: 0.3%) of strain, the modulus decreases considerable reaching 78.9MPa (SD:15.1MPa). In the final section of the curves, the samples have high deformation with a brittle final failure. The maximum average stress and strain are 70.0MPa (SD:10.0MPa) and 51.5% (SD: 7.6%). On the other hand, Figure 4b show the results of the tensile tests of PP reinforced with coated fibres. The samples have an average Young modulus of 6.0GPa (SD: 0.5GPa), a strength of 90.4MPa (SD: 7.7 MPa) and the strain at the maximum stress corresponds to 3.3% (SD: 0.3%).



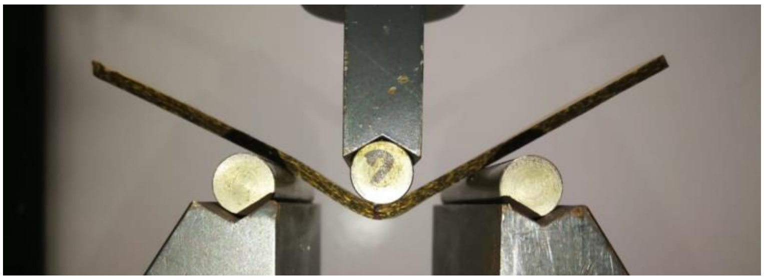
a) b)

Figure 4. Strain-strain curve obtained from tensile tests a) samples made of only PP, b) PP reinforced with coated Fique fibres.

4.2 Bending tests

For the bending tests, the samples are manufactured according to the method of section 3.3, using a rectangular mould of 190x120x3mm in height, width and thickness respectively. For the bending tests, 48 layers of PP are used, [PP_{48}], and the stacking sequence for PP-Fique laminates corresponds to [PP_2/Fique/PP/Fique/PP/Fique/PP/Fique/PP_2]. After hot-pressing, the samples are cut using a laser cutting machine, obtaining rectangular samples, see Figure 5a. The samples have a width of 14.8mm (SD: 0.4mm), a length of 170mm (SD: 1.2mm) and a thickness of 3.6mm (SD: 0.1mm). The tests are carried out using a three-point bending fixture as Figure 5b shown. The loading and support noses have a diameter of 10mm and the distance between the support noses is 60mm. For the tests, a displacement control crosshead speed of 2 mm/min is used.

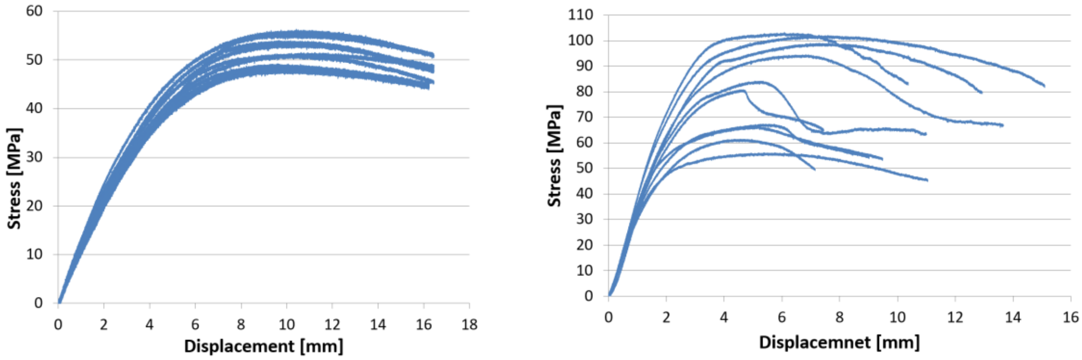
a)



b)

Figure 5. a) Samples for bending tests PP reinforced with coated Fique fibres b) three-point bending test.

Figure 6 shows the results of the bending tests. Despite the high dispersion obtained in the results using coated Fique fibres, the flexural strength and the Young modulus increase in comparison to the composites of only PP. The average flexural strength and the Young modulus of only PP are 51.4 MPa (SD: 3.0 MPa) and 2.0 GPa (SD: 0.2) respectively. On the other hand, for the PP composites reinforced with the coated Fique fibres, the strength is 81.5 MPa (SD: 17.8) and the Young modulus is 5.8 GPa (SD: 0.5).



b) **c)**

Figure 6 Bending tests results, a) only PP, b) PP reinforced with coated Fique fibres c) PP reinforced with uncoated Fique fibres.

4.3 Charpy impact tests

The samples correspond to an unnotched prismatic rectangular shape of 15mm in width, 50mm in length and 3mm in thickness with the same stacking sequence used for tensile tests. For the tests, a pendulum with a mass of 0.48kg with a drop high of 330mm and angle of 107.46 is used. The velocity of the pendulum just before the impact corresponds to 2.9m/s. The amount of energy dissipated for the Only PP samples is 275.1 J/m (SD: 21.6 J/m), while energy dissipated by the samples of PP reinforced with coated Fique fibres corresponds to 454 J/m (SD: 87.6 J/m).

5. Discussion and conclusions

Table 2 summarises the mechanical properties measured in tension, bending and impact tests. At the end of Table 2, the improvement in properties between results using only PP and the composites of PP reinforced with coated Fique fibres is shown. It is possible to see that despite the high dispersion found during the tests, the coated Fique fibres used as a reinforcement of PP laminate can contribute to obtain a better performance of the material reducing the amount of plastic needed in low loading applications.

Table 2: Summary of results.

	Tensile Test		**Bending Test**		**Charpy Test**
	Strength [MPa]	Y. Modulus [GPa]	Strength [MPa]	Y. Modulus [GPa]	Energy [J/m]
Only PP	70.0 (DS: 10.0)	2.8 (DS: 0.1)	51.4 (SD: 3.0)	2.0 (SD: 0.1)	275.1 (SD: 21.6)
PP & Coated Fique	90.4 (SD: 7.7)	6.0 (SD: 0.5)	81.5 (SD: 17.8)	5.8 (SD: 0.5)	454 (SD: 87.6)

Improvement [%]	29.0	111.5	58.5	187.6	65.0

The high variation in the results using fique fibres is produced because the manufacturing method is not completely standardised, especially the production of the laminates, being not available in the market a laminate of Fique fibre with high quality. The coating proposed in this work contributes to obtaining a better dispersion of the fibres in the composites, avoiding dry zones related to fibres agglomeration.

Acknowledgements

The authors acknowledge the financial support provided by the Royal Academy of Engineering and the Newton Fund: Industry-Academia Partnership Programme, IAPP18-19/29 and to the company Compañia de Empaques for providing the material using in this work. Author G. Idarraga would like to thank Colciencias of the Colombian government for the Doctoral grant, Colciencias, call 647 and The National University of Colombia.

6. References

1. Kumaran S, Shamprasad MS, Varadarajan YS, Sangamesha MA. Coconut coir fiber reinforced polypropylene composites: Investigation on fracture toughness and mechanical properties. Materials Today: Proceedings Volume 46, Part 7, 2021, Pages 2471-2476.
2. Ifuku S, Yano H. Effect of a silane coupling agent on the mechanical properties of a micro fibrillated cellulose composite. International Journal of Biological Macromolecules Volume 74, March 2015, Pages 428-432.
3. Khondker O, Ishiaku U, Nakai A, Hamada H. Fabrication and mechanical properties of unidirectional Jute/PP composites using Jute yarns by film stacking method. Journal of Polymers and the Environment, April 2005, Vol. 13, No. 2.
4. Mathijsen D. The renaissance of flax fibers. Reinforced Plastics, May/June 2018, Volume 62, No. 3.
5. Mathijsen D. Fully bio-based fiber reinforced thermoplastics can now challenge polypropylene composites. Reinforced Plastics, March/April 2021, Volume 65, No. 2.
6. Worldwide Textile Industry to 2026 - Increasing Demand for Natural Fibers is Driving Growth September 23, 2021 05:33 ET | Source: Research and Markets.
7. Global Natural Fiber Composites Market 2020-2024. $ 1.49 Billion Growth in Natural Fiber Composites Market During 2020-2024 | 38% Growth to Come from North America | Technavio. January 27, 2021. Source: www.businesswire.com
8. Wambua P, Ivens J, Verpoest I. Natural fibers: Can they replace glass in fiber reinforced plastics? Compos. Sci. Technol. 2003, 63, 1259-1264.
9. Santulli C. Mechanical and impact properties of untreated jute fabric reinforced polyester laminates compared with different E-glass fibre reinforced laminates. Science and Engineering of Composite Materials, 2000, Vol. 9, No 4.
10. Charlet K, Jernot JP, Gomina M. Mechanical properties of flax fibers and of the derived unidirectional composites. Journal of Composite Materials, 2000, Vol. 44, No. 24.
11. Ovalle S, Blanco C, Combariza M. Exploring the composition of raw and delignified Colombian fique fibers, tow and Pulp. Cellulose, 2018, 25:151–165.

12. Gómez C, Alvarez V, Gañán P, Vázquez A. Fique Fibers: Enhancement of the Tensile Strength of Alkali Treated Fibers During Tensile Load Application. Fibers and Polymers 2012, Vol.13, No.5, 632-640.
13. Castellanos LJ, Blanco-Tirado C, Hinestroza JP, Combariza MY. In situ synthesis of gold nanoparticles using fique natural fibers as template. Cellulose, 2012, 19:1933–1943.
14. Chacón M, Blanco C, Hinestroza JP, Combariza M. Biocomposite of nanostructured MnO2 and fique fibers for efficient dye degradation. Green Chemistry, 2013, 15, 2920.
15. Echeverri R, Franco L, González M. Fique en Colombia. Fondo Editorial ITM, diciembre de 2015.
16. Sezgin H, Kucukali-Ozturk M, Berkalp O, Yalcin-Enis I. Design of composite insulation panels containing 100% recycled cotton fibers and polyethylene/polypropylene packaging wastes. Journal of Cleaner Production, 2021, 304, 127132.
17. Ritchie H, Roser M. Plastic Pollution. Published online at OurWorldInData.org.
18. Belokon TD, Kurganova YA, Bragin DA, Kovalev MN. Increasing the efficiency of the recycling of propylene - polyethylene raw materials. Russian Metallurgy (Metally), Volume 2017, Issue 13, pp.1099-1102
19. Kim M, Park T, Hong S. Experimental determination of the plastic deformation and fracture behavior of polypropylene composites under various strain rates. Polymer Testing 93, 2021, 107010.
20. Ghasemi FA, Ghasemi I, Menbari S, Ayaz M, Ashori A. Optimization of mechanical properties of polypropylene/talc/graphene composites using response surface methodology. Polymer Testing 53, 2016, 283–292.
21. Bahlouli N, Pessey D, Raveyre C, Guillet J, Ahzi S, Dahoun A, Hiver JM. Recycling effects on the rheological and thermomechanical properties of polypropylene-based composites. Materials and Design, 33, 2012, 451–458.
22. Vargas J. Análisis interfacial de un material compuesto fabricado en matriz polimérica reforzado con fibras de fique para potenciar sus propiedades mecánicas. Master thesis, National University of Colombia, 2020.
23. McLean S. Fique fibre characterisation for use in composites and potential applications. Thesis BEng Mechanical Engineering, University of Strathclyde, 2019.

