

## Hybrid material of recycled plastics (PET and PP) and aggregates for the manufacture of sustainable paving blocks

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### Abstract

Sustainable construction requires innovative materials that minimize environmental impact and optimize resource use. Recycling widely discarded plastics such as polyethylene terephthalate (PET) and polypropylene (PP) offers a viable strategy to reduce waste accumulation and reliance on virgin resources. This study develops and characterizes a hybrid material made from recycled PET and PP combined with mineral aggregates for manufacturing eco-paving blocks intended for rural construction. Several mix proportions were tested, achieving compressive strengths of 20–25 MPa and flexural strengths near 10 MPa, values comparable to conventional concrete pavers but with significantly lower weight. Water absorption remained  $\leq 1\%$ , complying with Ecuadorian Standard INEN 3040 and European Standard UNE-EN 1338. The findings demonstrate that incorporating recycled plastics into paving blocks supports the circular economy, reduces plastic pollution, and provides lightweight, durable, and cost-efficient alternatives suitable for agricultural and rural infrastructure, contributing to more sustainable construction practices.

**Keywords:** sustainable construction; recycled plastics; hybrid materials; rural pavements

## Material híbrido de plásticos reciclados (PET y PP) y áridos para la fabricación de adoquines sostenibles

### Resumen

La construcción sostenible exige materiales innovadores que reduzcan el impacto ambiental y promuevan el uso eficiente de los recursos. El reciclaje de plásticos ampliamente desechados, como el tereftalato de polietileno (PET) y el polipropileno (PP), surge como una estrategia viable para disminuir la acumulación de residuos y la extracción de recursos vírgenes. Este estudio desarrolla y caracteriza un material híbrido elaborado a partir de PET y PP reciclados combinados con áridos para fabricar eco-adoquines destinados a edificaciones rurales. Se evaluaron distintas proporciones de mezcla, obteniéndose resistencias a compresión de 20–25 MPa y resistencias a flexión cercanas a 10 MPa, valores comparables a los de adoquines de hormigón, pero con un peso significativamente menor. La absorción de agua fue  $\leq 1\%$ , cumpliendo con la NTE INEN 3040 y la norma europea UNE-EN 1338. Los resultados evidencian que incorporar plásticos reciclados en elementos constructivos impulsa la economía circular y ofrece materiales livianos, resistentes y de bajo costo adecuados para infraestructura rural sostenible.

**Palabras clave:** construcción sostenible; plásticos reciclados; materiales híbridos; pavimentos rurales.

## 1 Introduction

The increasing accumulation of plastic waste represents one of the most critical environmental challenges of the 21st century. Globally, millions of tons of single-use plastics, such as polyethylene terephthalate (PET) and polypropylene (PP), end up in landfills or in natural environments, generating severe impacts on ecosystems and human health. Faced with this problem, the circular economy approach proposes sustainable strategies such as reuse, recycling, and recovery of materials to extend their useful life cycle and reduce pressure on natural resources.

In 2021 alone, the global production of plastics increased by 4% more than the previous year, to over 390.7 million tons, after stagnation in 2020 due to the Covid-19 pandemic, demonstrating the continued demand for this material [1].

Despite the growing concern of environmental activists regarding global plastic pollution, the demand for plastics is expected to continue to increase. In 2021, the packaging sector had the largest share at 44%, followed by building and construction (18%), automotive (8%), electrical and electronics (7%), household, leisure and sports (7%), agriculture, livestock and gardening (4%), and others (12%), as shown in Figure 1. This is attributed to modern lifestyle, consumerism, and the fact that we are not yet fully aware of the problem that is generating the indiscriminate accumulation of plastics worldwide [2,3].

However, not everything is negative in the world of plastics; there are waste management initiatives that need support from different public and private entities, since recycling rates worldwide are still low. Lack of technology, poor resource management, lack of coherent programs, and incomplete processing of plastics have made this problem more pronounced [4,5].

Because of this, plastics recycling represents a promising option to achieve zero waste and climate-neutral production, requiring investment and innovation by the plastics value chain to develop new business models for reuse. Thus, expanding the use of recycled plastic can support the development of new technologies that depend less on fossil-based materials and contribute to reducing plastic waste accumulation in dumps, landfills, forests, rivers, and other ecosystems.

Since mechanical recycling of plastics requires less capital and fewer resources, it can be an appropriate waste management option, particularly in developing countries such as Ecuador. An important strategy for consuming this waste material is its use in rural construction projects, as recycled plastics demonstrate good mechanical strength, durability, resistance to gas penetration, low weight, ease of installation, low cost, and broad availability, making them suitable for the manufacture of a variety of products [6–7].

In construction, plastics are used in plumbing, siding, flooring, insulation, paneling, doors, windows, glazing, bathroom units, gratings, railings, and a growing range of structural as well as interior and decorative applications. However, rural buildings, unlike urban ones, must meet very specific conditions determined by their environment, socio-cultural factors, and the industries being exploited. The dwellings occupied by rural families often form an integrated unit with agricultural and livestock facilities.

This context provides a wide range of opportunities for facilities related to farming and food storage, such as corrals, terraces, reservoirs, irrigation systems, food storage tanks, silos for grain preservation, and other spaces where the use of safe, recycled plastic-based materials could be highly beneficial.

The present research seeks to address this need by providing flooring materials for rural constructions that are non-toxic, lightweight, low-cost, moisture-resistant, and demonstrate optimum physical and mechanical properties for use in a variety of applications in both housing and livestock or agricultural facilities. Two types of plastic waste were used: polypropylene (PP) and polyethylene terephthalate (PET), combined with aggregate materials to produce eco-friendly paving blocks.

The project was carried out within the framework agreement between the Centro Integral de Manejo de Residuos Sólidos del Municipio de Loja (Integrated Solid Waste Management Center of the Municipality of Loja) and the Universidad Nacional de Loja–Ecuador (National University of Loja), aiming to raise awareness of the feasibility of using waste materials to develop new building materials, thereby contributing to reducing plastic pollution, conserving natural resources, and promoting the circular economy.

## 2 Materials and methods

The city of Loja, Ecuador, has a garbage collection and classification system carried out by the Municipality of Loja. Polypropylene (PP) and polyethylene terephthalate (PET) bottles and containers were obtained from the Integrated Solid Waste Management Center of the Municipality of Loja, which is administered by this governmental entity. The fine and coarse aggregates were obtained from the Yamba Quarry, Malacatos parish, canton Loja–Ecuador. Ethyl alcohol ( $C_2H_6O$ , 70%) was purchased from Sigma-Aldrich for cleaning the plastics.

### 2.1 Obtention and preparation of raw materials

Polyethylene terephthalate (PET) and polypropylene (PP) plastic bottles and containers were collected from the Integrated Solid Waste Management Center of the Municipality of Loja (Fig. 1).



Figure 1. Integrated Solid Waste Management Center of the Municipality of Loja. Source: Own elaboration

Table 1.

Plastic particle size	
Size of screen diameter	Dimensions (mm)
Grande	0.5
Mediano	0.25
Pequeño	0.1

Source: Own elaboration

Table 2.

Proportion of PET and PP plastic mixture for the elaboration of eco-paving blocks.

% Recycled plastic mix	PET	PP
		100
	75	25
	50	50
	25	75
	0	100

Source: Own elaboration

To ensure a clean and controlled surface free of mineral salts and impurities that may interfere with the adhesion and thermal-mechanical behavior of the recycled plastic matrix, distilled water was used in the washing process instead of regular tap water. The plastic waste was washed with distilled water, soap, and 70% ethyl alcohol three times and then dried at room temperature ( $\pm 21^\circ\text{C}$ ) for 48 hours.

## 2.2 Plastic waste shredding process

For the shredding of the plastic material, a blade shredder was used, consisting of a hopper or inlet, a motor, and a rotor with blades and a sieve or screen. The screen was positioned to allow smaller pieces of plastic to pass through during the shredding process. The screen sizes are shown in Table 1.

Once the material was crushed, it was subjected to an oven drying process for 24 hours or until reaching a moisture content  $\leq 1\%$ .

## 2.3 Preparation of the eco-paving blocks

An extrusion process was used to manufacture the eco-paving blocks. The worm screw extruder consisted of a hopper for material input, a motor, a rotor, a cylinder or barrel, a 100 cm long worm screw, a head, and a nozzle of varying diameter. A working temperature range of  $160^\circ\text{C}$  to  $260^\circ\text{C}$  was established, taking into account the melting temperature of both polymers.

First, preliminary tests were carried out on blends between recycled PET (a very fragile and brittle polymer) and PP (a material with greater flexibility after reheating). The blends were prepared in the proportions shown in Table 2.

Each of the mixes was made in duplicate and evaluated for percentage water absorption, moisture, density, compressive strength, and flexural strength.

Based on preliminary tests, the 50:50 PET:PP blend was selected, then combined with different sizes of aggregate material in three proportions: 75:25%<sub>PLASTIC:AGGREGATE</sub>, 50:50%<sub>PLASTIC:AGGREGATE</sub>, and 25:75%<sub>PLASTIC:AGGREGATE</sub>. For each treatment, two replicates were analyzed, and the five aforementioned variables were measured.

The fine and coarse aggregates used in this study were obtained from the Yamba Quarry, located in Malacatos

Table 3.

Particle size of aggregates.

AGGREGATES	PARTICLE SIZE
(FINE AND COARSE)	LARGE ( $\pm 10$ MM)
	MEDIUM ( $\pm 5$ MM)
	SMALL ( $\pm 3$ MM)
	VERY SMALL ( $\pm 1$ MM)

Source: Own elaboration

parish, Loja-Ecuador. Four particle sizes were utilized: large ( $\pm 10$  mm), medium ( $\pm 5$  mm), small ( $\pm 3$  mm), and very small ( $\pm 1$  mm). These aggregates were washed, sieved, and oven-dried to  $\leq 1\%$  moisture, as shown in Table 3.

The melted mixtures were placed in stainless-steel molds with internal dimensions of  $200\text{ mm} \times 100\text{ mm} \times 60\text{ mm}$ , following the specimen preparation requirements established in NTE INEN 3040:2016 for precast concrete paving units [8].

### 2.3.1 Aggregate characterization

Although aggregates from the Yamba Quarry are generally siliceous and calcareous in mineral nature, this study did not include a detailed chemical composition analysis of the aggregate material.

## 2.4 Study variables

### 2.4.1 Compressive strength (C)

The compressive strength test was performed following UNE 41410 [9].

Compressive strength is the maximum stress that a material can withstand under a crushing load, which is calculated by dividing the maximum load by the original cross-sectional area of a specimen in a compression test.

### 2.4.2 Total water absorption rate (AA)

The water absorption rate was measured following the NTE INEN 3040:2016 standard [8]. This method consists of impregnating the test specimen ( $M_i$ ) with water and then suspending it in a container with water for 24 hours. The surface water of the specimen is dried and its weight ( $M_s$ ) is taken, after which the specimen is placed in an oven at  $100^\circ\text{C}$  for 24 hours and the weight reading ( $M_d$ ) is taken again.

The water absorption rate is expressed as the difference between the weight of the saturated specimen minus the weight of the dry specimen and the weight of the dry specimen, expressed as a percentage. The following Eq. (1) is used to calculate the water absorption:

$$AB (\%) = \frac{M_s - M_d}{M_s - M_i} \times 100 \quad (1)$$

Where:

$M_s$  = mass of the saturated unit (kg)

$M_i$  = mass of the submerged unit (kg)

$M_d$  = mass of the oven-dried unit (kg)

### 2.4.3 Flexural strength (RF) and ultimate load at room temperature ( $\pm 21^{\circ}\text{C}$ ), cold ( $\pm 10^{\circ}\text{C}$ ), and hot ( $\pm 30^{\circ}\text{C}$ )

The flexural tensile test was performed following the procedure established in the UNE-EN 1338 [10] standard for precast concrete paving units, which defines the method for evaluating bending resistance through center-point load application. The flexural tensile test consists of the application of a vertical force (P) at a defined speed to the center of the specimen placed horizontally on two supports (L) until the specimen breaks (F). Eq. (2) is used to obtain the value of the bending tensile strength:

$$f = \frac{3PL}{2bh^2} \quad (2)$$

Where:

- f = flexural tensile strength (Mpa)
- P = breaking load (N)
- L = span between supports (mm)
- b = tile width (mm)
- h = tile thickness (mm)

### 2.4.4 Moisture content (H)

To calculate the moisture content of the entire unit at the time the received mass is determined (when Mr is measured), the following equation (3) is used:

$$H (\%) = \frac{Mr - Md}{Ms - Md} \times 100 \quad (3)$$

Where:

- Mr = mass of the unit as received (kg)
- Ms = mass of the saturated unit (kg)
- Md = mass of the oven-dried unit (kg)

The above calculation of moisture content is only applicable to the whole unit at the time the as-received mass is determined.

### 2.4.5 Density ( $\rho$ )

The following equation (4) was used to calculate the density of the oven-dried unit;

$$D (\text{kg}/\text{m}^3) = \frac{Md}{Ms - Mi} \times 1000 \quad (4)$$

Where:

- Md = mass of the oven-dried unit (kg)
- Ms = mass of the saturated unit (kg)
- Mi = mass of the submerged unit (kg)

## 3 Results

### 3.1 Plastic particle size

The plastic particle diameter size of 0.25 mm (Fig. 2) was selected for the production of the eco-paving blocks. This

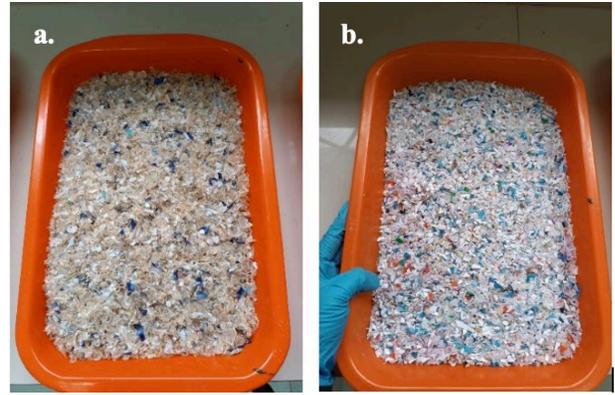


Figure 2. Plastic waste a. polyethylene terephthalate (PET) and b. polypropylene (PP). Source: Own elaboration



Figure 3. Eco-pavers in their different plastic-to-aggregate ratios. Source: Own elaboration

size was selected because it is the optimum size to work within the temperature range during the melting process of PET ( $260^{\circ}\text{C}$ ) and PP ( $160^{\circ}\text{C}$ ), avoiding the decomposition of the plastics during heating and ensuring the preservation of their physical-mechanical and thermo-elastic properties.

### 3.2 Characterization of the eco-paving blocks

The mixing ratio of the two types of plastic used for the elaboration of the eco-paving blocks was 50:50%<sub>PET:PP</sub>, as they withstand greater loads under compressive and flexural stress.

This ratio was combined with each size of aggregate material in three proportions: 75:25%<sub>PLASTIC:AGGREGATE</sub>, 50:50%<sub>PLASTIC:AGGREGATE</sub>, and 25:75%<sub>PLASTIC:AGGREGATE</sub>. For each treatment, two replicates were carried out, and five variables were analyzed. Fig. 3 shows the eco-paving blocks in their different plastic:aggregate ratios.

Through the determination of the water absorption percentage, it could be observed that all proportions present an absorption rate of  $\pm 1\%$ , which is within the permissible limits under the Ecuadorian Standard NTE INEN 3040 [8] for concrete pavers used for paving in force since 2016 (limit

< 6%). Likewise, the European Standard UNE-EN 1338 [10] for precast concrete and cement pavers states that the appropriate limit is up to 6% for climatic resistance or water absorption. A water absorption value lower than 6% ensures good resistance to low temperatures and frost. As a result, all combinations of eco-paving blocks are suitable to withstand the required design stresses and ensure optimum service life. The results are shown in Table 4.

Within agricultural constructions, a low percentage of water absorption guarantees the suitability of these blocks for facilities such as sheds, storage buildings, silos, tanks, irrigation canals, and irrigation systems. A low absorption rate ensures good floor management in livestock facilities and reduces farmers' maintenance efforts.

Since soil is one of the most commonly used materials in agricultural construction floors, eco-paving blocks made from recycled plastic can become an economical and safe alternative for better farm management. For floors that need to prevent cattle from slipping in corrals and that absorb humidity—but require periodic replacement—plastic materials represent a more durable option. This type of eco-paving block can also be used as an alternative to plastic ramps or other materials that could be costly for small producers, for example in pig fattening.

The density test was part of the water absorption test. The density of the eco-paving blocks (Table 5) directly influences the degree of resistance to factors such as weight, friction, or abrasion, and depends on the materials and proportions used in manufacturing. In the case of the eco-paving blocks, it could be observed that the density values were similar, averaging 1,900 in spite of the different sizes of sand aggregate.

This may be due to the fact that the weight and quantity of the aggregate influence the final value of density. A smaller aggregate particle size allows a greater amount of material to be incorporated into the eco-paving blocks, whereas a larger aggregate particle size results in fewer particles being incorporated. Thus, there is an inverse relationship between particle size and the amount of aggregate per block. This explains the different density results of plastic:aggregate mixtures.

Table 5 shows the results of the density analysis of the eco-paving blocks in proportions 50:50% PLASTIC:AGGREGATE in the four particle sizes.

Table 4. Water absorption rate (AB), density (ρ), and humidity (CH%).

	Stone Size	Aggregate (%)	Plastic (%)	AB (%)	CH (%)	P (kg/m3)
50:50% PET:PP	Large (±10 mm)	25	75	0.80	10.00	1,970
		50	50	0.67	10.00	1,975
		75	25	0.65	20.00	1,977
	Medium (±5 mm)	25	75	0.70	12.50	1,974
		50	50	0.89	25.00	1,969
		75	25	0.63	20.00	1,978
	Small (±3 mm)	25	75	0.87	10.00	1,967
		50	50	0.72	20.00	1,975
		75	25	0.67	11.11	1,975
	Very small (±1 mm)	25	75	1.05	18.18	1,963
		50	50	0.83	20.00	1,970
		75	25	0.86	10.00	2,169

Source: Own elaboration

Table 5. Density of eco-paving blocks in proportions 50:50% PLASTIC:AGGREGATE for the four particle sizes.

Particle size	Mix	ρ (kg/m <sup>3</sup> )	
Grande (±10 mm)		1,963	1,975
Mediana (±5 mm)	50:50%	1,961	1,969
Pequeña (±3 mm)	plástico:árido	1,958	1,975
Muy Pequeña ±1 (mm)		1,964	1,970

Source: Own elaboration

Comparing the density values obtained for eco-paving blocks and conventional concrete blocks, which range from 2200–2400 kg/m<sup>3</sup>, it can be observed that the eco-paving blocks can be suitable for rural constructions, with the advantages of being lighter and having a high level of resistance to climatic and external factors (heat, cold, etc.), durability of the structure, adaptability of shapes, and reduced risk of deformation.

Through compression and flexural-tensile analyses (Table 6), it was possible to determine that the eco-paving blocks have good compressive strength, with values between 18 and 25 MPa. These results indicate that compressive strength is independent of the proportions of recycled plastic and aggregate. In addition, the variation in particle size did not affect compressive strength. The small aggregate ratio (±3 mm) produced the highest compressive strength values of 22.8 MPa, 23.05 MPa, and 25.07 MPa for the three ratios: 75:25% PLASTIC:AGGREGATE, 50:50% PLASTIC:AGGREGATE, and 25:75% PLASTIC:AGGREGATE, respectively.

The flexural strength of the eco-paving blocks ranged from 4.27 MPa to 11.55 MPa. Based on these results, it can be deduced that blocks with a higher percentage of recycled plastic exhibit greater flexural strength. This was consistent across the tests carried out at room temperature (±21°C), cold (±10°C), and hot (±30°C). The data obtained also exceed those established in the Spanish Standard UNE-127022 for concrete tiles, which specifies a minimum resistance of 3.5 MPa.

According to Anton et al. (2020), in their study of flexural strength of recycled plastic reinforced mortar pedestrian tiles, an average flexural strength of 3.66 MPa was obtained after 28 and 56 days. In a similar study of flexural strength in glazed tiles exposed to freeze-thaw cycles, Solano (2017) reported an average value of 24.7 MPa in each cycle evaluated.

Table 6. Compressive strength (RC) and flexural strength (RF) at room temperature (±21°C), cold (±10°C), and hot (±30°C)

Stone size	Stone %	Plastic %	RC (Mpa)	RF(Mpa)			Col d ± 10° C
				Room ±21°C	Hot ± 30°C		
50:50 PET:PP	Large (±10 mm)	25	75	22.27	5.06	7.79	11.55
		50	50	23.10	8.96	5.22	6.46
		75	25	15.63	4.27	5.41	5.37
	Medium (±5 mm)	25	75	19.05	6.53	4.99	5.70
		50	50	20.19	6.48	7.24	6.39
		75	25	24.99	9.03	7.51	7.63
	Small (±3 mm)	25	75	25.07	9.83	5.87	10.46
		50	50	22.80	10.73	5.30	10.72
		75	25	23.05	7.03	6.69	8.31
Very small (±1 mm)	25	75	18.16	5.01	3.30	5.81	
	50	50	21.30	9.30	6.11	6.56	
	75	25	20.19	7.66	5.41	9.04	

Source: Own elaboration

## 4 Conclusion

All constructions and facilities that support the agricultural sector are essential for the proper development of productive activities. The eco-paving block, manufactured from waste plastic and aggregates, constitutes a prefabricated material that can be used in livestock and agricultural constructions. Its potential applications should be studied in greater depth due to their impact on farmers' daily activities and on environmental conservation.

Furthermore, the results of this study establish parameters of safety, economy, and environmental preservation criteria, showing that the best combination was observed for the PET:PP 50:50 mixture with an aggregate particle size of  $\pm 3$  mm, in its three proportions: 75:25%<sub>PLASTIC:AGGREGATE</sub>, 50:50%<sub>PLASTIC:AGGREGATE</sub>, and 25:75%<sub>PLASTIC:AGGREGATE</sub>.

## References

- [1] Darko, C., Shi-Yung, P.W., Chen, A., Acquaye, A., Review and recommendations for sustainable pathways of recycling commodity plastic waste across different economic regions. *Resources, Environment and Sustainability*, 14, Art. 134, 2023. DOI: <https://doi.org/10.1016/j.resenv.2023.100134>
  - [2] Hyuni, J., Giyoung, S., Hojung, K., Lam, T.H., Jonggeon, J., Hyo, J.K., Hyeonyeol, J., Jeyoung P., Dongyeop X.O., Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste. *Chemosphere*, 320, Art. 138089, 2023. DOI: <https://doi.org/10.1016/j.chemosphere.2023.138089>
  - [3] Ramin-Tolou, J., Ali, H., Alireza, M., Using woven recycled plastic fibers in reinforced concrete beams. *Construction and Building Materials*, 404, Art. 133262, 2023. DOI: <https://doi.org/10.1016/j.conbuildmat.2023.133262>
  - [4] Abang, S., Wong, F., Sarbatly, R., Sariau, J., Baini, R., Awang-Besar, N., Bioplastic classifications and innovations in antibacterial, antifungal, and antioxidant applications. *Journal of Bioresources and Bioproducts*, 8(4), pp. 361-387, 2023. DOI: <https://doi.org/10.1016/j.jobab.2023.06.005>
  - [5] Sierra-Montes, L.F., Bioplásticos activos biodegradables en suelo para aplicaciones agronómicas. In *Encuentro de Becarios de Grado y Posgrado de la UNLP (EBEC)*. La Plata, 20 de noviembre de 2024.
  - [6] Fan, X., Yu, Z., Yi-Fan, Y., Shi-Qi, L., Xi, W., Ying, Y., Yun-Xiang, X., Bioplastics with high mechanical strength, transparency, chemical stability, and recyclability by introducing dynamic ester bonds and rigid benzene rings into natural rubber. *Polymer*, 337, Art. 128956, 2025. DOI: <https://doi.org/10.1016/j.polymer.2025.128956>
  - [7] Farah, S.S., Thinesh, S.B., Mohamed-Thariq H.S., The evolution and environmental prospects of renewable bioplastics: types, production methods, and sustainability. *Journal of Renewable Materials*, 13(6), pp. 1071-1101, 2025. DOI: <https://doi.org/10.32604/jrm.2024.02024-0011>
  - [8] NTE-INEN, 3040: Concrete Paving Units—Requirements and Test Methods. Instituto Ecuatoriano de Normalización, 2016.
  - [9] UNE, 41410, Concrete—determination of compressive strength.
  - [10] UNE-EN 1338, Precast concrete paving flags—requirements and test methods.
  - [11] Antón, N., González-Fernández, Á., and Villarino, A., Reliability and mechanical properties of materials recycled from multilayer flexible packages. *Materials*, 13(18), 3992, 2020.
  - [12] Solano, E.F., Pedroza, J.B., y Roa, S.A.Q., Evaluación de la resistencia a la flexión en baldosas esmaltadas de cerámica en función de los ciclos de hielo y deshielo. *Revista colombiana de tecnologías de avanzada (RCTA)*, 1(25), pp.92-98. 2017.
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