Experimental design with gypsum composite material, reinforced with "Carloduvica Palmata"

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Abstract. In this research, a new gypsum composite material, reinforced with Carloduvica Palmata plant fiber, is developed for use as prefabricated panels in interior spaces. An experimental methodological design with a quantitative approach is used, since the study variables will be manipulated until the desired physical characteristics are achieved. The first step is to obtain the natural fiber from local suppliers, then a treatment consisting of: washing, chemical purification, bleaching and crushing. The fibers are classified according to their length and diameter, and then specimens are made with different compositions of gypsum and organic material to perform flexural and compression tests in a specialized laboratory. The analysis with the specimens revealed that the L2 fiber (12 x 1 mm) with a density of 3% in the mixture obtained the best compression and flexural results, demonstrating that both the 36 mm and 1 mm elongated fibers are of lower resistance. Similarly, the panels were fabricated with this material and were found to have superior characteristics compared to a conventional gypsum panel. Also, the physical appearance of the reinforced panel does not differ from conventional panels, so it may represent a possible substitute. Conclusion: the use of biodegradable materials in the manufacture of construction materials represents a more environmentally friendly process to reduce the risk of environmental pollution and greater energy efficiency.

1 Introduction

The Construction Industry (CI) in Ecuador is currently one of the most booming commercial sectors at present, this statement can be verified through the data provided by the National Survey of Buildings (ENED) who reported that, only in 2019, the construction of 33,314 new buildings and 47,291 new homes were projected in the country in a land area of more than 14.0 million square meters [1]. As mentioned by the Central Bank of Ecuador [2], although CI is good news for the country's economy, since it represents the third most lucrative commercial activity that contributes up to 7.22% to the national GDP, the truth is that this industry is one of the most polluting, since its execution involves pollution and waste of natural resources and contributes to the emission of greenhouse gases [3].

Based on the contributions made by Gutiérrez et al. (2021) [4], worldwide, the construction industry is considered one of the main sources of environmental pollution, as it is directly involved in the waste and contamination of drinking water in cities with up to 16%

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of all the water in the world [5]. Also, the massive manufacturing of inputs, materials and secondary activities that derive from it such as transportation increase the carbon footprint of these activities. [6]. Currently, this activity is intrinsically related to the generation of highly environmentally polluting solid and liquid waste, the massive extraction of natural resources, the generation of micro particles in the air due to demolition, and the consumption of water, energy, and natural resources for the development and manufacture of construction materials [7].

According to [8] the traditional construction materials used, contribute significantly to the pollution of the environment of this country, since, according to the SIGMAPRO database (2022) the processes involved in the creation of construction materials at present can contribute up to 67 GWP100a per year to global warming [9]. However, as mentioned by Hernández et al. (2021) [5], it is possible to significantly minimize the ecological impact of CI by substituting some materials with biodegradable raw materials that reduce greenhouse gas emissions and have a biodegradable characteristic [8].

In this regard, Flores (2021) [1] alludes in his research that the creation of new biodegradable materials encourages the production not to use many energy resources and to reuse materials that were discarded from other industrial processes [10] and [11]. An example of this, is the use of Carloduvica Palmata fiber or better known in Ecuador as toquilla straw, a resource widely used to make handmade fabrics, and with greater consumption in high-end hats known worldwide [1]. According to Padilla et al. (2014) [12] Carloduvica Palmata fiber can be used as a natural reinforcement of construction elements due to its mechanical properties, especially if they are composites of materials used in construction such as gypsum [13].

Gypsum is an element that has been present in construction for more than 7 000 years, according to archaeologists; since the 18th century, the study of this material begins with a scientific basis and the industrialization process is developed through which the manufacturing process is controlled, the products are standardized and some additives are incorporated. On the other hand, there is a set of properties and advantages that make gypsum stand out among other materials and make it continue to be used today as a construction element, since this material is easily mouldable, light and aesthetic, a good thermal and acoustic insulator; it is fire resistant and its cost is low compared to other materials.

Also, based on the contributions of Gonzalez et al. (2019) [10] the purpose of plant fibers, is to improve the mechanical properties of a construction material, since otherwise they would be unsuitable for practical applications. The main advantage of reinforcing with plant fibers as the gypsum matrix, is the behaviour obtained from the composite material after matrix breakage to determine the mechanical properties of this new composite material of gypsum and Carloduvica Palmata [11].

The post-breakage strength provided by the fibers could allow a more intensive use of these materials in the construction field, due to their improved mechanical properties such as ductility, flexibility and resistance to breakage of the resulting material. If we consider that the construction industry is one of the most polluting industries in the world, causing irreparable environmental damage, without considering an alternative natural material for its replacement [14].

In view of the aforementioned problems, this research project and proposal of a new material performs an experimental design to efficiently mix gypsum with Carloduvica Palmata to determine the main mechanical properties from bending and compression tests, designing a more environmentally friendly construction system through life cycle analysis, in a developing city like the city of Cuenca.

2 Materials and methods

The methodological strategies used for the elaboration of the entire research, as well as the data collection and analysis instruments, are presented below.

2.1 Methodological Design

The present research uses an experimental methodological design with a quantitative approach, since the study variables will be manipulated until the desired physical characteristics are achieved. The experimental method consists of a whole process of observation, manipulation and recording of the variables that make up a study phenomenon to understand the reasons for its facts, in this case, the portions and mixture and dimensions of the materials are going to be manipulated until a final product that adapts to the necessary characteristics required by the researcher is achieved [7].

Regarding the quantitative method, comments that it is a methodology that uses statistics and other mathematical strategies to analyze a variable and characterize its components whose data can later help to find the solution to a specific problem. In the case of this study, numerical information is collected from test trials to find the mixture that represents the best mechanical characteristics [15].

2.2 Moulding Technique

The methodology used for moulding corresponds to "hand lay-up", which is a manual technique used for composite materials that has the characteristic of performing the entire procedure with an open mould, but with the environmental conditions duly conditioned and controlled to avoid contamination and mixing with external materials.

2.3 Fiber Production

The fiber is obtained through local traders in the city of Cuenca, from a plant of the palm family that grows between 2 and 3 meters high and is particularly found in the coastal area of Ecuador, specifically in Manabi and Santa Elena, widely used in the handicraft area, so it has a lot of liquid in its cellular structure and it is necessary to give it a treatment before its use [16].

For its use the "Carloduvica Palmata", is harvested from its 3 years of life, this particular plant has no trunk, the palms or leaves grow up to 1.5 m long, [16]. They are cut by hand with machete and then with an instrument popularly known as „uñal” begins to defibrate the leaf in such a way that "buds" are obtained to then be processed 50 by 50 depending on the size of the tank for the procedure called lignocellulosic.

2.4 Fiber Treatment

In this section we present all the phases carried out for the treatment of the fiber before starting with the mixtures in their different compositions.

First phase, washing: During 1 hour the toquilla straw is kept submerged in water at boiling point, together with another component which is sulphur to achieve a natural cream colour and not green. During this time, the fiber is constantly moved so that in the process a uniform colour of the vegetable is obtained. It is then washed with accumulated water from the rain or nearby rivers to remove the remaining residues, then it is dried in the open air for 2 days in the sun.

Second phase, fiber purification and chemical treatment: The main objective of chemical treatments is to eliminate non-cellulosic components such as waxes, pectin, inorganic components that form the lumen of the fiber, additive substances, to transform the fiber surface [17]. To carry out a correct chemical treatment, it is necessary to establish a quality control of the raw material (Carloduvica Palmata fiber) delimiting parameters related to the chemical composition (cultivation conditions, plant area, etc.).

Third phase, bleaching: the fiber was then subjected to a bleaching process: in a volume of water of 7 m^3, with 10 kg of Hydrogen Peroxide, 8 kg of Tripoli Phosphate, for 16 kg of woven toquilla straw, it was kept in the sun for 3 spring days in a geo-referenced location: from 10 am to 4 pm for the purification of the fiber.

Fourth phase, shredding: the shredded toquilla straw in its purified state (chemical treatment) obtains a better result for the required construction terms, i.e. greater adherence and very low water absorption, avoiding the formation of fungi at the time of setting of the composite. In the shredding process, 3 types of fibers are obtained in terms of thickness, volume and dimension, of which 3 samples are taken from the result of passing through a sieve (see Fig. 1).

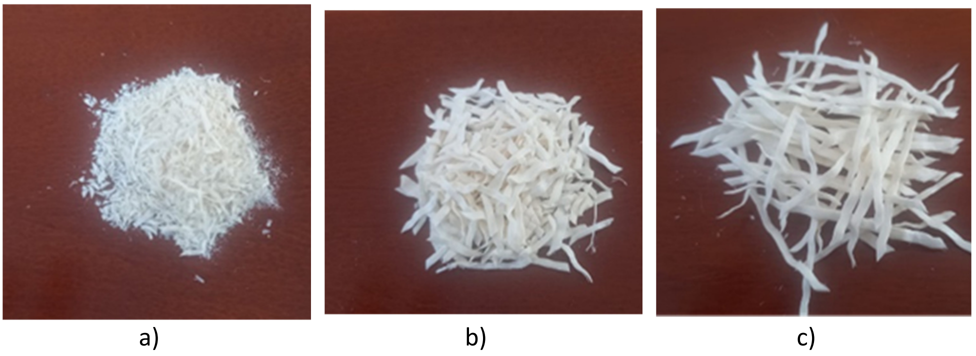

Fig. 1. Fiber shredding. Note: A) 1 mm long by 0.05 mm thick, L1, B)12 mm by 1.0 mm thick, L2, and C) 36 mm by 1.2 mm thick, L3. Source: Own elaboration

2.5 Test Specimen Processing

Twenty specimens made of gypsum reinforced with processed toquilla straw were manufactured for compression tests, 20 specimens for flexural tests and 2 gypsum specimens, thus guaranteeing a level of reliability higher than 90% in the statistical analysis of the results. The materials were weighed using a digital balance.

After weighing the materials to ensure the desired percentages, the mass is prepared and placed in the moulds. For the preparation of the composite with gypsum matrix, the correct preparation of the mass in laboratory containers was considered in order to obtain the best mechanical and chemical properties. The composite material with toquilla straw vegetable fiber reinforcement was left to rest in the moulds for 24 hours so that it would set properly.

Subsequently, the specimens were put to dry in the oven at 25+/-2 degrees Celsius for 7 days, to reach the constant mass condition as established by NBR 12129. A German-made universal testing machine with a load capacity of 100 kN was used to carry out the compression and flexion tests (see Fig. 2).

Fig. 2. Testing machine.

2.6 Flexural Test

According to EN 196-1 (Methods of testing cement) the flexural strength can be measured by the three-point bending test. A testing machine with a 10.0 KN load cell was used. The instrument is equipped with two steel support rollers with a spacing of 100 mm and a diameter of 10 mm. A third steel roller, of the same diameter and placed centrally to apply the load P. The test was performed by actuating the displacement of this roller, which moved at a speed of 0.05 mm per minute (see Fig. 3).

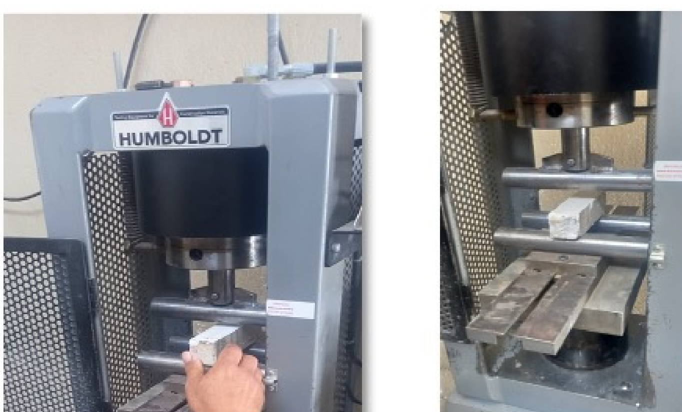

Fig. 3. Flexure testing process

The same test instrument, but with a different support, was also used to determine the compressive strength. The apparatus consists of a stimulation device (see Fig. 4).

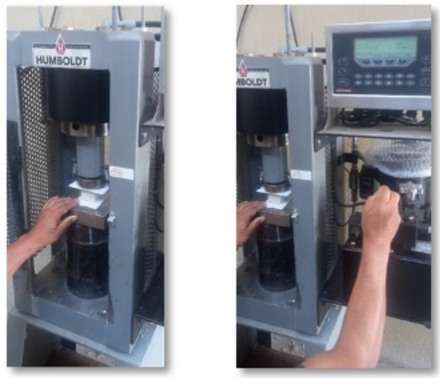

Fig. 4. Flexure testing process.

To facilitate load control and two auxiliary steel plates, with a thickness of 10mm and a load area of 40 x 40 mm^2. The compression load P is increased smoothly at a rate of 200 N per second until failure. In this project, the percentages of toquilla straw fiber were taken into account for the analysis of the samples (18) in order to obtain better results (author 2019): 1%; 2%; 3% are the percentages of toquilla straw and gypsum as matrix, used for the preparation of the samples, whose prismatic specimens according to ASTM standards for testing composite materials are: 40 x 40 x 160 mm (author2020) for flexural tests and 40 x 40 x 40 mm for compression tests.

3 Results

For the presentation of the results, we start with the data provided by the testing machine program. Fig. 7 shows the flexural strength test for the 1% fiber specimens, where the L2 composition of 12 x 1.0 mm obtained the highest resistance to the deflection exerted

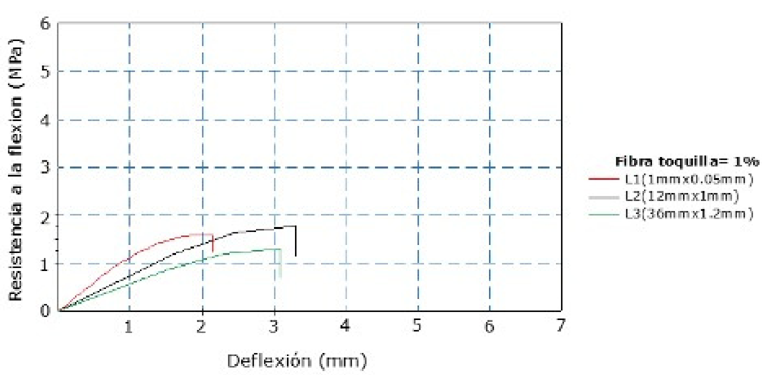

Fig. 5. 1% fiber flexural strength test.

On the other hand, as shown in Fig. 6, in the bending strength test with 2% fiber, sample L2 of 12 x 1.0 mm obtained the highest resistance to the deflection exerted.

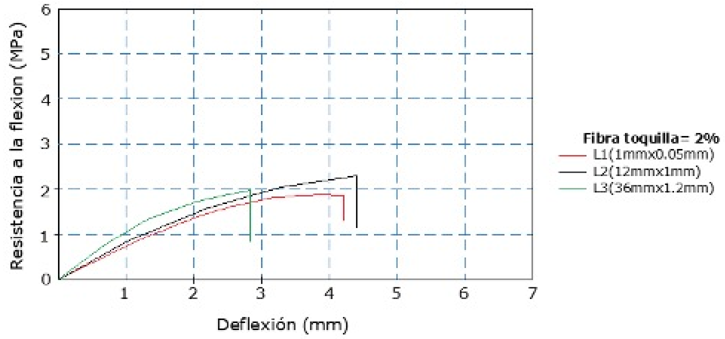

Fig. 6. Flexural strength test with 2% fiber.

Fig. 7 shows that in the flexural strength test with 3% fiber, sample L2 of 12 x 1 mm obtained the highest resistance to the deflection exerted.

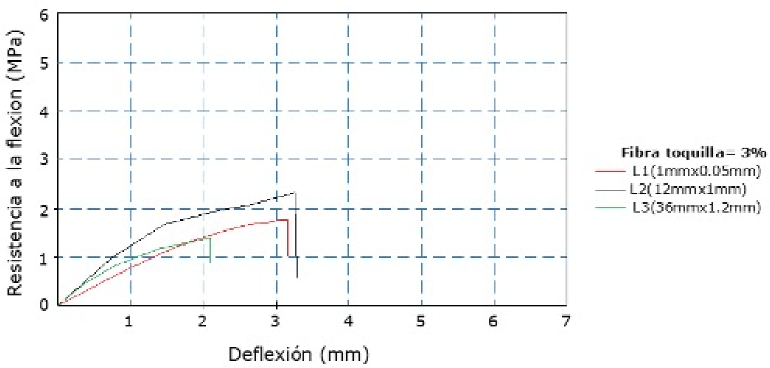

Fig. 7. 3% fiber flexural strength test.

In Fig. 8 in the 1% fiber compressive strength test the 36 x 1.2 mm specimen L3 obtained the highest strength against deformation, however, specimen L2 deformed significantly more with similar strength to L3.

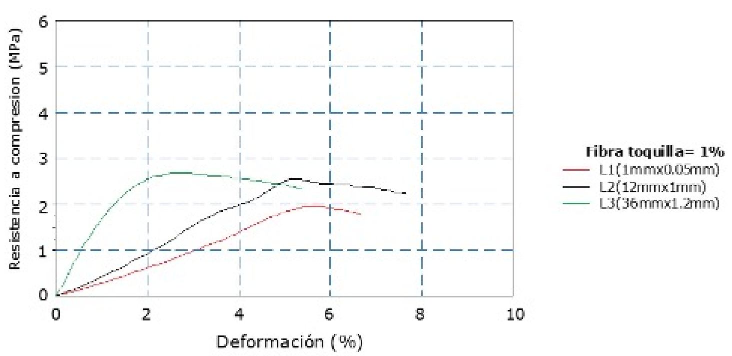

Fig. 8. 1% fiber flexural compression test.

In Fig. 9, in the compressive strength test with 2% fiber, sample L2 of 12 x 1 mm obtained the highest resistance to the deformation exerted.

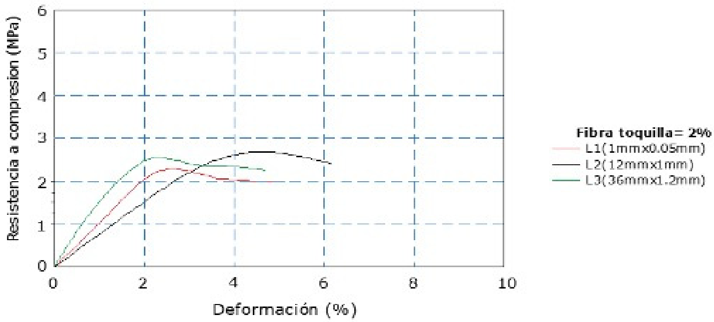

Fig. 9. Flexural compression test with 2% fiber.

In Fig. 10, in the compressive strength test with 2% fiber, sample L2 of 12 x 1 mm obtained the highest resistance to the deformation exerted.

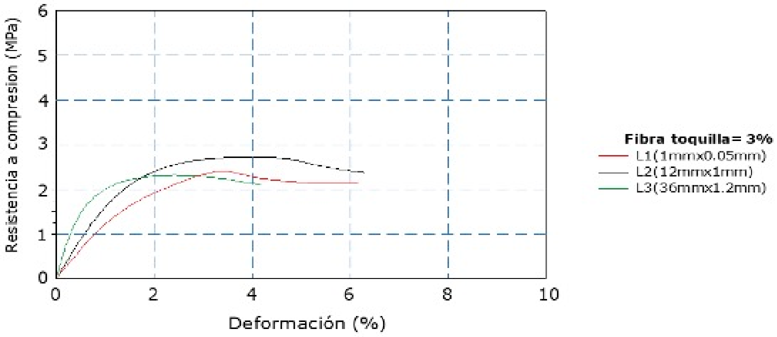

Fig. 10. Flexural compression test with 3% fiber.

In order to improve the interpretation of the results, Table 1 shows the data collected from the tests and compared with each other. As can be seen in the table, during the experimentation it was determined that the L2 fiber with a percentage of 3% obtained the best results in compression and bending, demonstrating that both the 36 mm and 1 mm elongated fibers are of lower resistance.

Table 1. Strength in compression and bending tests

Fiber Blanket	Type of test / type of fibre	L1	L2	L3
		1 x 0.05 mm	12 x 1 mm	36 x 1.2 mm
1%	Compression strength [MPa]	1.95	2.55	2.67
	Flexural strength [MPa]	1.60	1.78	1.32
2%	Compression [MPa]	2.30	2.67	2.55
	Flexural strength [MPa]	1.87	2.31	2.02
3%	Compression [MPa]	2.41	2.72	2.29
	Flexural [MPa]	1.77	2.33	1.39

3.1 Panel Development (Process)

To make the gypsum panels, the percentages of water + gypsum established by the standards were followed, in which the water-gypsum ratio was considered, using the saturation mixing method. In the same way, the percentage of organic aggregate that obtained the best results in the tests was used, that is to say, with 3% fiber. To make the panel as a sample for this project, a cylindrical glass container, a stopwatch and a precision balance were used. Pour into the container 2000 grams of water and 4 000 grams of gypsum and 3% of this value in toquilla fiber L2.

Then, the gypsum is sprinkled in the glass container with water, until after 90 seconds the paste reaches about two millimetres below the water. The compound is moved until a uniform paste free of air bubbles is obtained, when the compound begins to take effect, this is no more than 2 minutes, the percentage of the bleached toquilla straw fiber is poured into the container, it is mixed again and then poured into the mould, and with a 60 mm rod it is tapped 15 times on each side of the mould to avoid air bubbles inside the new compound. Fig. 11 shows the panel reinforced with the completely dry organic aggregate [14].

Fig. 11. Carloduvica Palmata reinforced gypsum composite panel

Similarly, Fig. 12 shows a visual comparison between the panel with aggregate and a commercial gypsum panel, as can be seen there are some differences in colon, but the texture is similar, as well as the compacted and the feel to the touch. An extra benefit of the panel with aggregate is that being a more greyish colour it will be much easier when painting compared to the commercial one.

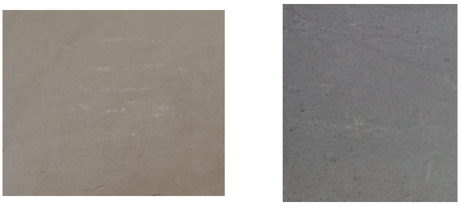

Fig. 12. Gypsum composite panel reinforced with Carloduvica Palmata.

4 Discussion

Tests carried out on gypsum specimens with different percentages of vegetable fiber additions showed that there is a proportional relationship between the percentage of fiber and the flexural and compressive strength. One explanation for this phenomenon is that the fiber acts as a structural mesh that provides greater adherence to the gypsum composite preventing it from crumbling easily [18] and [19]. These results can be compared with the data presented by Martinez (2020) [14] who made gypsum panels reinforced with different natural fibers including a variety of Carloduvica Palmata. Among the results found by the author, it can be evidenced that the percentage of fiber had a significant positive influence on the flexural and compression tests, finding a proportional relationship between 4.5 to 6 MPa when adding up to 2% of fiber.

On the other hand, it was observed that the fiber length also had a strong influence on the results, since the longer the aggregate was, the better the flexural strength. However, no positive relationship was found between fiber length and compression, since the longer the fiber, the lower the compressive strength. These effects are explained by the same fiber arrangement, since the loads that produce bending act perpendicularly to the aggregate axis causing a deformation that is mostly supported by the fiber, therefore, the longer it is, the better its resistance. On the contrary, the effects of compression cause the specimens to deform in its central area, therefore, a longer fiber will have to deform in this area and will have a lower resistance.

Regarding the aesthetic aspect of the panel, no significant difference could be appreciated since the gypsum did not change colour and the size of the fibers did not visually affect the entire composition. In addition, it should be taken into account that products with gypsum usually have a paperboard lining or external coatings that reduce to zero the possible visual impact of the product already installed.

5 Conclusion

After performing the theoretical and contextual inquiry of information researched in the main digital repository of the network, it was found that the construction industry, especially the sector responsible for the manufacture of inputs and construction materials are one of the industries that most pollute the environment due to carbon emissions produced in factories, pollution in rivers and lakes by the waste generated and the use of compounds that are not biodegradable and pollute the place where they are deposited. However, it was possible to prove that the pollution inherent to this industry can be reduced by implementing biodegradable compounds in its structure.

After characterizing the flexural and compressive strength of the gypsum specimens with organic aggregate in a specialized laboratory, it was possible to verify that the compound with a percentage of 3% obtained the best results and it was demonstrated that both the 36 mm and 1 mm elongated fibers are of lower strength. Likewise, it was observed that the chemical bleaching process significantly improved the adhesion of the fiber with the plaster, as well as the water absorption was lower relative to the unprocessed fiber.

It was demonstrated that it is possible to make a gypsum panel with organic aggregate compounds that improves the resistance compared to a commercial panel and that can be used to decorate interiors in construction activities. Likewise, by having an organic fiber composite, when its useful life is over, its degradation process improves, thus reducing its contamination.

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