Manufacturing and mechanical characterization of eco-friendly blocks using organic waste as aggregate

Fabricación y caracterización mecánica de bloque ecológico empleando desechos orgánicos como agregado

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Key Handbooks

Propose a new composite material using organic waste for the construction of ecological block with low environmental impact. The properties of the material, including its composition and mechanical characteristics, are fundamental. It is also crucial to consider construction norms and standards, ensuring that the test methods and parameters evaluated comply with applicable national standards. On the other hand, the manufacturing method, process design, material selection and optimisation play a key role. These aspects form the basis for generating and consolidating knowledge to foster future research in the development of environmentally friendly materials. The results of the compression tests indicate that the evaluated samples do not meet the minimum simple compressive strength requirement of 2 MPa (equivalent to 20.39 kg/cm²). Samples with 2.5% fibre content have a compressive strength range of 11.1 to 18.74 kg/cm², which is below the minimum required value. The base sample, without fibre content, shows a slightly higher compressive strength, reaching 19.01 kg/cm².

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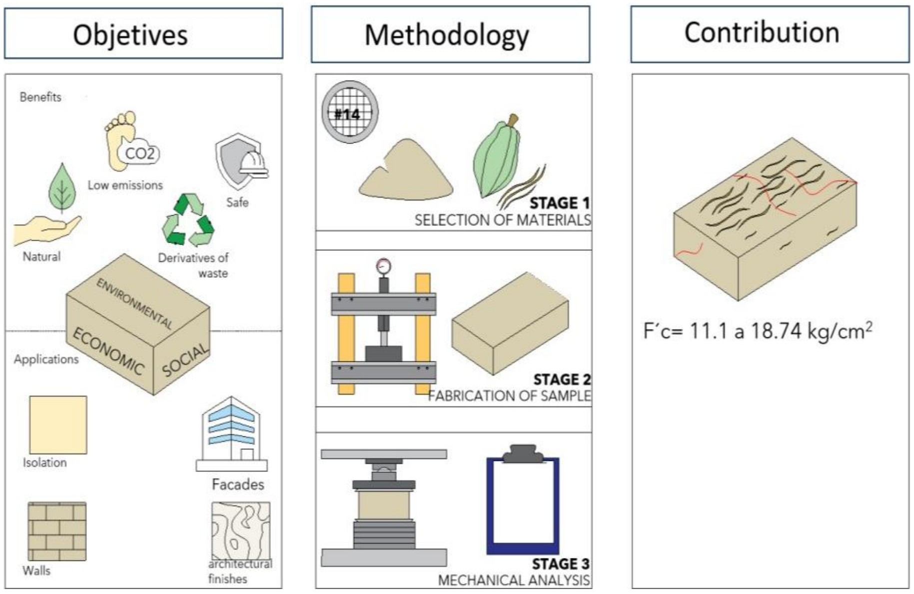
Abstract

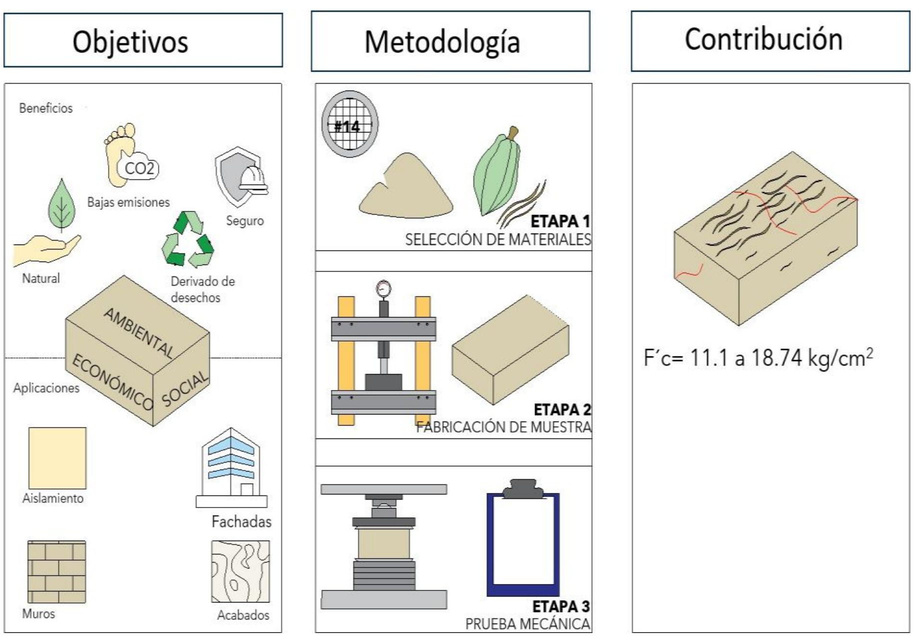
Population growth and the demand for habitable spaces have turned construction into a critical challenge for environmental sustainability. This industry, characterized by its high dependence on raw materials, not only depletes natural resources but also leads to ecosystem degradation and pollutant emissions. Therefore, it is essential to research new materials that not only comply with industry regulations but also reduce environmental impact and promote more sustainable practices. Currently, eco-blocks are emerging as a viable alternative with significant environmental benefits. This work establishes the methodology for manufacturing an ecological block using natural fibers considered as waste as aggregate and determines its mechanical properties. Additionally, the compressive strength obtained is compared with other materials available on the market and those reported in the literature to assess its potential.



Mechanical properties, natural fibers, eco-blocks

Resumen

El crecimiento de la población y la demanda de espacios habitables han convertido la construcción en un desafío crítico para la sostenibilidad ambiental. Esta industria, marcada por su elevada dependencia de materias primas, no solo agota los recursos naturales, sino que también provoca la degradación de los ecosistemas y emisiones contaminantes. Por ello, es fundamental investigar nuevos materiales que no solo cumplan con las normativas del sector, sino que también disminuyan el impacto ambiental y fomenten prácticas más sostenibles. Actualmente, los eco-bloques se presentan como una alternativa viable con significativos beneficios medioambientales. En este trabajo, se establece la metodología para la fabricación de un bloque ecológico empleando fibras naturales consideradas desecho como agregado y se determinan sus propiedades mecánicas. Además, se comparan fuerza de compresión obtenida con otros materiales disponibles en el mercado y aquellos reportados en la literatura, con el fin de identificar su potencialidad.



Propiedades mecánicas, Fibras naturales, Eco-bloques

Introduction

The environmental impact of the construction industry is alarming, as it originates mainly from the massive extraction of natural materials, greenhouse gas emissions, excessive primary energy consumption and the production of unmanaged waste (Aghimien et al., 2019). This sector is a major source of greenhouse gas emissions, mainly due to the industrial processes required for the production of cement and other building materials. These processes, which include extraction, transportation and manufacturing, generate a significant amount of emissions, and, perhaps most critically, waste generation (López Ruiz et al., 2020).

Cement is used to make concrete and mortar, and is the second most consumed compound on the planet (Scrivener et al., 2018). Concrete is used to build homes, schools, hospitals, workplaces and infrastructure for human development. The raw materials used in the manufacture of cement are obtained mainly through quarrying for the extraction of hard rocks such as limestone, slate and certain shales. In some cases, the deposits are exploited by underground methods (International Energy Agency, 2018; Scrivener et al., 2018).

The process of making cement is well established and has hardly changed since it was first developed almost 200 years ago (Hart, 2022). The process is shown in Figure 1 and consists of three stages: the first is extraction of raw materials and their preparation, the second stage can be defined as hot cycle or Clinker production and finally cold cycle, where Clinker is mixed with other components such as gypsum for cement production (Hart, 2022). Clinker is normally a mixture of limestone (calcium carbonate) and siliceous materials (clays) which are heated in a kiln to temperatures of around 1450 °C, this phase releases direct CO_2 emissions. Between 30% and 40% of emissions are produced by burning fuels and 60-70% come from chemical reactions (Fayomi et al., 2019).

Box

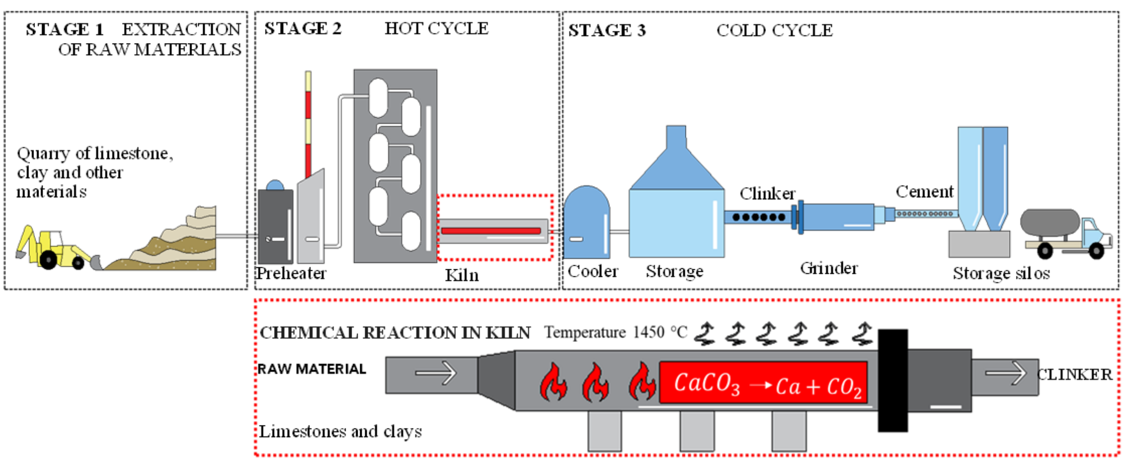


Figure 1
Cement production process and chemical reaction

Source: *Own elaboration*

The cement sector is the third largest energy consumer in the industry, more than 90% of the energy required for cement manufacturing is obtained from fossil fuels, while the remaining 10% is obtained from electricity (Aghimien et al., 2019). The industry's energy consumption is accounting for 7% of global energy consumption, equivalent to 10.7 exajoules (1EJ=10^{18} J). The concern for energy alternatives and more efficient production processes stems from the fact that 30% to 40% of total emissions come from fuel combustion (International Energy Agency, 2018). The most commonly used fuels in the cement industry were coal, coke or heavy oils (Müller et al., 2008).

Global population growth and urbanisation patterns, together with increasing demand for infrastructure, will drive an increase in demand for cement and concrete. Currently, the production of one tonne of cement generates between 0.65 and 0.95 tonnes of CO_2, depending on the efficiency of the process (Müller et al., 2008). By 2050, global cement production is estimated to increase by 12-23% from the current level (International Energy Agency, 2018).

The global cement industry faces the challenge of ensuring its commercial viability while reducing its carbon intensity. This requires transformations in production processes, optimising fuel use and developing new materials that minimise environmental impact.

Actions taken in the building industry can have an immediate impact on global climate change, as well as on energy consumption and economic and social consequences (Chen et al., 2024; Oberle et al., 2019). While these strategies can help the building sector move towards sustainability by promoting innovative solutions that integrate environmental awareness, such as smart concrete, it is critical to recognise that emissions are linked to the production process (Tian et al., 2024). Advances in materials can be integrated with innovative production methods and technologies as well as old construction methods that often offer environmental benefits.

The incorporation of sustainable building materials in projects worldwide aims not only to combat climate change, but also to promote awareness in construction. It can also generate significant economic savings by improving the methodology and application of life cycle costing (LCC), particularly in the construction, maintenance and operation sections (Liu et al., 2022).

Until the mid-19th century, buildings were mainly constructed with natural materials such as wood, adobe, earth and local fibres. Subsoil construction is one of the oldest techniques, being the basis of early dwellings and cities, which used raw earth to create simple shelters from easily accessible materials (Touré et al., 2017). Even today, in many parts of the world, earthen buildings can still be found, often combining this material with other materials to improve their resistance (Jesudass et al., 2020; Pacheco-Torgal & Jalali, 2012). Natural fibres, in particular, offer great potential in the field of civil construction, as they can contribute to more sustainable architecture in the future (Balasubramanian et al., 2024). This would not only allow for a greater diversity of building materials, but also encourage design innovation and the improvement of conventional materials (Steffens et al., 2017). Fibres act as mechanical reinforcement, especially in terms of tensile and flexural strength in concrete (Hamada et al., 2023).

Methodology

In Figure 2, the three stages that make up the research methodology applied in this study are illustrated in detail. Each stage reflects a key step in the fabrication, characterisation, analysis and interpretation of data, ensuring that the results obtained are relevant and reliable for the context of the study.

Box 2

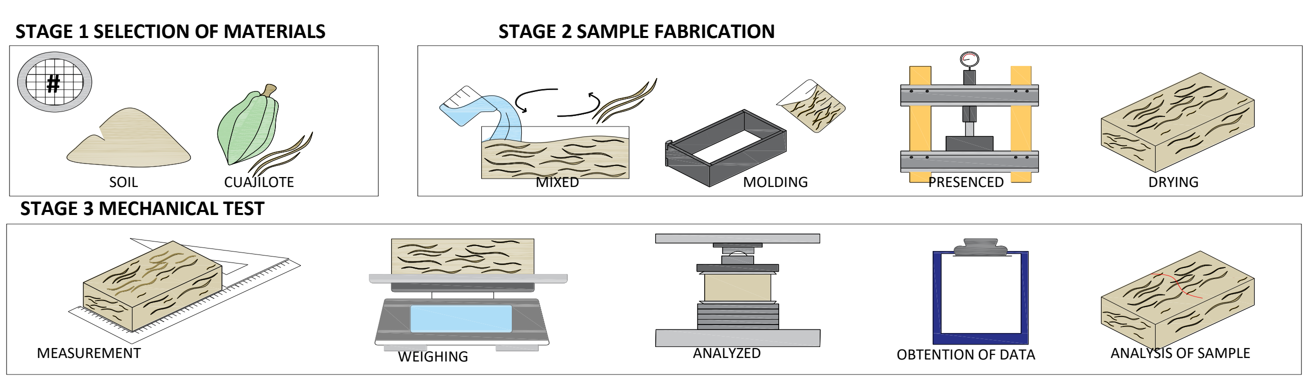


Figure 2
Methodology applied

Source: *Own elaboration*

Stage 1 Selection of materials

Choice of soil

Sahcab or saskab was used as a base material, which is considered an abundant limestone soil in the Yucatan peninsula, and is one of the most widely used materials in construction. This soil can be in the form of gravel or silty sand, it is of sedimentary origin and its chemical composition consists mainly of calcium carbonate (Alonzo et al., 2006). The material was sieved on a #14 stainless steel mesh with an aperture of 1.40mm (0.0555").

Choice of aggregate

Parmentiera aculeata, also known as cuajilote or tree cucumber, was used as an aggregate for the ecological block. This species is widely distributed in southern Mexico and is found in Chiapas, Tabasco and Campeche. The 'cuajilote' tree can produce more than 600 fruits in a single year (Hellmuth, 2023). The cuajilote produces fibrous fruits with a high content of lignocellulosic compounds, based on the 'Study of the cellular architecture and micromechanical properties of cuajilote fruits. Using different microscopy techniques', where the micromechanical properties of the fruit were analysed, demonstrating that the orientation of the fibrils can help to improve mechanical properties for future applications (Vicente et al., 2021). Previously dried and separated into strands ≤30cm.

Stage 2. Sample fabrication

The design of the block was stipulated under the standard N-CMT-2-01-001/02, which defines the standardised parameters for working the sample. This standard contains the quality requirements for bricks and ceramic blocks that are used in ceramic bricks and blocks used in masonry structural elements. Table 1 presents the specifications applicable in this research.

Box 3

Table 1

Applicable block specifications under N-CMT-2-01-001/02- Standard N-CMT-2-01-001/02- Standard N-CMT-2-01-001/02- Standard N-CMT-2-01-001/02

Ranking	**Manufacturing**	**by hand**
	Subtypes	Massifs: Usually do not develop ceramic bonds and are only massive..
	Quality grades	E
Dimensions	Length	28-18
	Width	13.5 - 18.5
	Perch height	6 - 8.5
Use	**Structural requirements [1].**	Suitable for simple or reinforced non-supporting masonry with low axial compressive loads.
	Climatological requirements	Suitable only for mild climates with low rainfall
	Functional requirements	Not acceptable for externally visible walls without cladding.
Physical characteristics	**Simple compressive strength; MPa, minimum**	2
	Adhesion; MPa, minimum	0.15
	Water absorption %, maximum	24

For the execution of the mixture it will be manually weighed, with a proportion in percentage of 2.5% of fibre, with 30% of water, placed in a steel mould of 8x14x22 cm and subjected to pressure by means of a hydraulic press. It was demoulded and dried in the ambient conditions of the laboratory.

Stage 3. Mechanical test

This test was stipulated under the NMX-C-404-ONNCCE-2012 standard and was complemented with the Mexican standard NMX-C-036-ONNCCE which establishes the test method for the determination of compressive strength, which is based on the ASTM C-140-75 standard.

Sample analysis

The sample or specimen is tested in a universal testing machine (Figure 3), which must have sufficient capacity to operate at the specified loading rate without impact or loss of load. One of the blocks of the machine should have a hemispherical seat resting on the top of the specimen, while the other block should be rigid and provide a stable base for the specimen. It is essential to incorporate clamping or compression fittings that are rigid and correctly aligned. The centre of the sphere must coincide with the centre of the bearing surface with an appropriate tolerance to the radius of the sphere. The compression surfaces of the specimens must be flat, complying with a tolerance of 0,05 mm over a length of 150 mm taken in two orthogonal directions.

Box 4

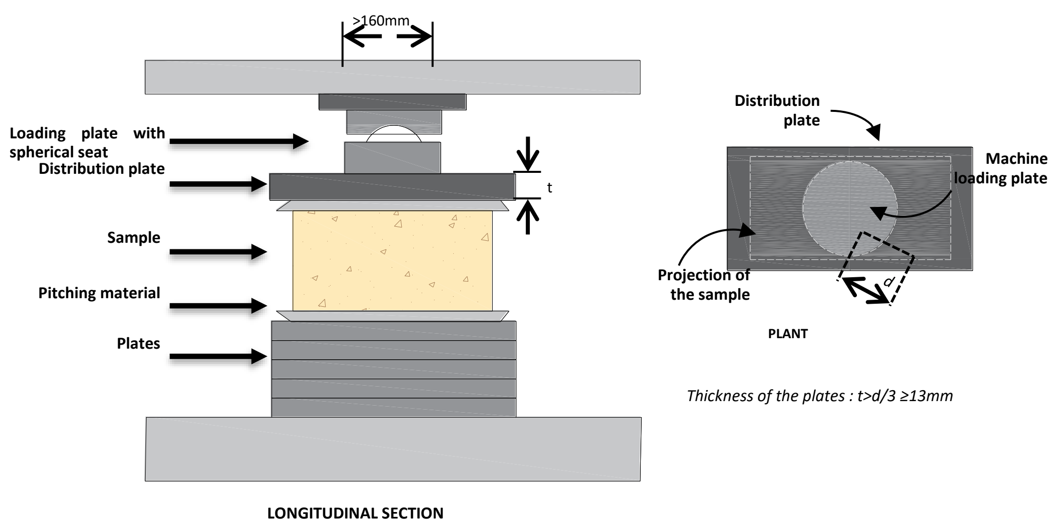


Figure 3
Compression test preparation Source: Own elaboration

Calculations

$$R = \frac{F}{A} \quad [1]$$

Where:

R Is the compressive strength in MPa ($^{Kgf/cm2}$)

F is the maximum load in N (Kgf)

A Is the cross-sectional area of the specimen (cm^2)

Results

XRD soil characterisation

Figure 4 presents the characterisation of the soil carried out by means of an X-Ray Diffraction (XRD) equipment using a copper X-ray source (Cu-Kα), with an energy of 8.04 keV and an X-ray wavelength of 1.5406 Å. This technique allows detailed information to be obtained on the crystalline structure, composition and various physical properties of the analysed soil. In this case, the data obtained in the analysis show a 99% agreement with the CaCO3 reference standard, which confirms that the sample is mainly calcium carbonate. This result indicates that the Ca^{2+} and $CO3^{2-}$ ions are in a 1:1 ratio, linked by an ionic interaction. From the database, it indicates that its crystalline structure is hexagonal, whose plane with the highest intensity corresponds to the 10

Box 5

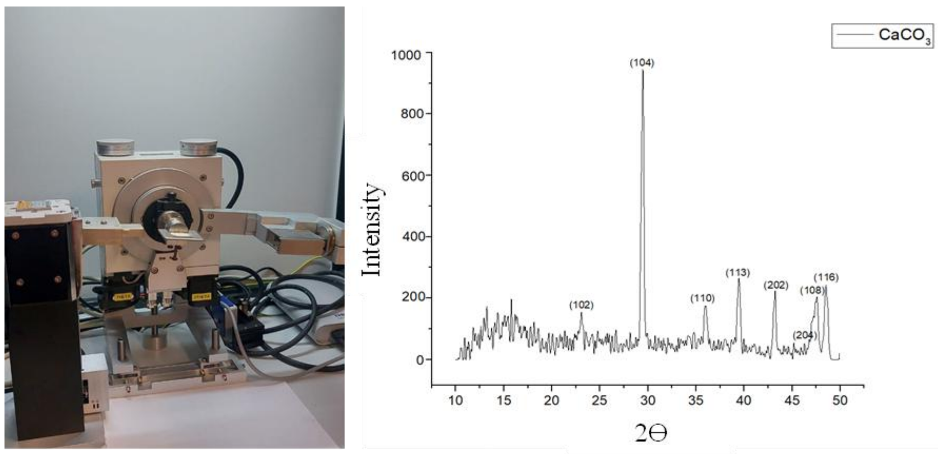


Figure 4
Characterisation by XRD

Source: *Own elaboration*

Sample

Prior to the mechanical compression test, the samples with 2.5% curd fibre content (figure 5) were analysed after 28 days, obtaining data such as: length, width, height and dry weight (table 2). The Mexican standard NMX-C-038- ONNCCE was used to obtain specific data for the block.

Box 6

Figure 5
Sample with 2.5% fibre

Source: *Own elaboration*

In table 2 we present the data of the analysed blocks, categorised as BASE, block or blank whose fibre percentage is equal to zero, while F1B1 2.5% refers to the block whose base is the sahcab and B1 the curd fibre, with 2.5% we refer to the percentage of aggregate. The pieces called F1B1 2.5% A, B, C, D are the sectioned pieces of a block.

Box 7

Table 2
Data obtained from samples under the NMX-C-038-ONNCCE standard

DATES	BASE	F1B1 2.5%	F1B1 2.5% A	F1B1 2.5% B	F1B1 2.5% C	F1B1 2.5% D
Length:	21.4cm	21.3cm	5.87cm	8.75cm	5.71cm	5.5cm
Width:	7.5cm	7.4cm	5.5cm	4.16cm	4.27cm	4.32cm
Height:	13.62	13.62	4.09	5.32	4.71cm	4.82cm
Weight:	3.950 kg	3.4 kg	.205 kg	.295 kg	.175 kg	.180 kg

Mechanical compression test

The samples are subjected to compression analysis in a universal machine, where the strength of the blocks is evaluated when they are compressed under a load. Because of the dimensions, the BASE and F1B1 2.5% samples are subjected to the preparation shown in figure 3, while the F1B1 2.5% A, B, C and D samples are tested directly from the spherical bearing plate. It is important to note that specimens A and B will be tested under the force of one direction of compression, while specimens C and D under another direction.

Box 8

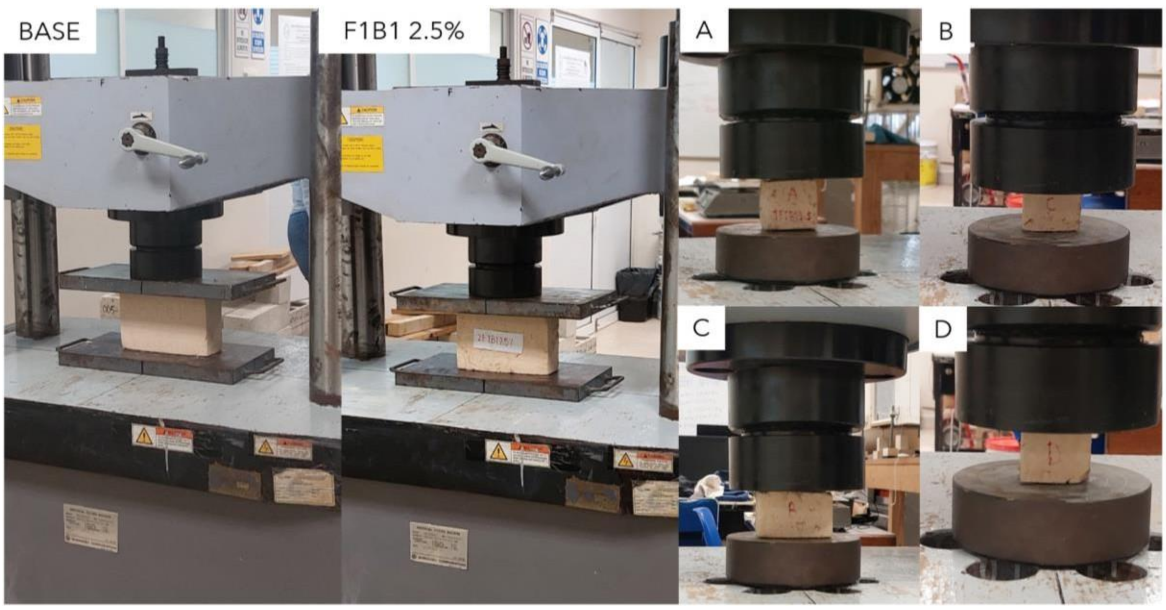


Figure 4
Mechanical compression test

Source: *Own elaboration*

In table 3, we obtain the capacity of the blocks to withstand the compressive forces, the gross area was obtained from the data obtained in table 2, and the maximum load is the data obtained from the universal machine, which gives us a detailed report. With equation 1, we obtain the data on the compressive strength of the samples.

Box 9

Table 3
Data obtained from the mechanical test

Sample	Long (mm)	Width (mm)	Gross area (cm²)	Carga Max. (Kg)	Kgf/cm²
BASE	214	75	160.5	3070.91	19.1
F1B1 2.5%	213	74	157.6	2183.35	13.9
F1B1 2.5% A	58.7	55	32.3	360	11.1
F1B1 2.5% B	87.5	41.6	36.4	426.57	11.7
F1B1 2.5% C	57.1	42.7	24.38	396	16.2
F1B1 2.5% D	55	43.2	23.76	445.395	18.74

It is important to understand that each specimen was loaded to failure and showed unique behaviour during the test (figure 6). For example, sample BASE shows medium-sized cracks distributed throughout the block; as it does not contain fibre as an aggregate, the piece tends to fragment. In contrast, sample F1B1 with 2.5% fibre presents cracks in several parts of the block, but thanks to the addition of fibre, the block maintains its cohesion, avoiding a total detachment of the parts. In samples A, B, C and D, the cracks are larger; however, the fibre present in the mix prevents the sections from detaching, which reinforces the integrity of the material even after the appearance of cracks.

Box 10

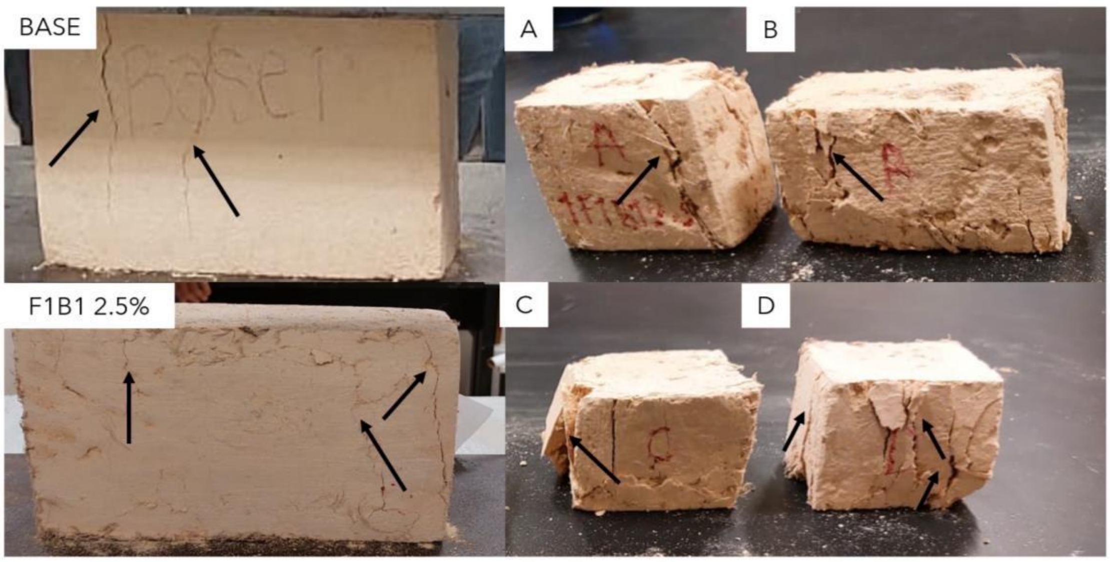


Figure 6
Samples after the failure

Source: *Own elaboration*

Conclusions

In conclusion, the results of this investigation and the data obtained from the compression tests reveal that the samples evaluated do not reach the minimum simple compressive strength parameter stipulated at 2 MPa (equivalent to 20.39 kg/cm^2). The samples with a fibre content of 2.5% have a compressive strength range of 11.1 to 18.74 kg/cm^2, lower than the minimum required. In comparison, the base sample, without fibre content, achieves a slightly higher compressive strength of 19.01 kg/cm^2.

The compression test also reveals that the addition of fibre in the samples improves the cohesion of the material and its resistance to splitting, even after the appearance of cracks. This suggests that the use of fibre not only contributes to controlling the size and distribution of cracks, but also strengthens the material's ability to withstand loads and resist crumbling, holding together structurally in the face of failure.

The weight difference between the BASE specimen and the F1B1 specimen with 2.5% fibre is approximately 13.92%. This indicates that the incorporation of fibre at this rate contributes to a small reduction in raw material usage. These results suggest the addition of a percentage of cement for future research to meet the parameters set by the standard.

Statements

This chapter focuses on the manufacture and mechanical characterisation of the ecoblock, in compliance with the applicable national regulations. This research represents a key step towards reducing the environmental impact generated by the construction industry. The adoption of eco-friendly materials in this sector poses a significant challenge, as it requires the integration of technical, regulatory and scientific expertise to ensure their performance.

Conflict of interest

The authors declare that they have no conflicts of interest. They have no financial interests or personal relationships that could have influenced this book.

Authors' contribution

Muñoz-Talango, Dayana G.: conducted the experimental tests, interpreted the results and wrote the manuscript.

Abatal, Mohamed:. Conceptualisation of the research topic and review of results.

Santiago- de la Cruz, Arlette A.: Revision of the hand-written manuscript.

Availability of data and materials

Data are available on request from the lead author.

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Abbreviations

Ca	Calcium
$CaCO_3$	Calcium carbonate
CO_2	Carbon dioxide
CO_3	Carbonate
cm^2	Square centimetres
EJ	Exajoules
Kgf	Kilogram-force
Kgf/cm^2	Kilogram-force per square centimetre

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