processes

MDPI

Article

Experimental and Statistical Analysis of Concrete Eco-Cobble Using Organic and Synthetic Fibers

Ricardo Andrés García-León *, Jorge Trigos-Caceres, Natalia Castilla-Quintero, Nelson Afanador-García and July Gómez-Camperos

Programas de Ingeniería Civil y Mecánica, Facultad de Ingeniería, Universidad Francisco de Paula Santander Ocaña, Ocaña 546552, Colombia; jetrigosc@ufpso.edu.co (J.T.-C.); ncastillaq@ufpso.edu.co (N.C.-Q.); nafanadorg@ufpso.edu.co (N.A.-G.); jagomezc@ufpso.edu.co (J.G.-C.)

* Correspondence: ragarcial@ufpso.edu.co; Tel.: +57-3152898250

Abstract: The environmental impact of traditional construction materials necessitates the development of sustainable alternatives. This study evaluates eco-cobbles as novel building materials designed to reduce environmental footprint while maintaining performance standards. The objectives were to develop an eco-friendly cobble alternative and assess its effectiveness through laboratory tests. Eco-cobbles were synthesized using recycled and bio-based materials and tested for compressive strength, flexural strength, and water absorption at 14 and 28 days. The compressive strength ranged from 11.5 MPa to 26.8 MPa, with a maximum value observed at 28 days in a mixture containing 95% concrete and 5% polyethylene terephthalate (PET). Flexural strength varied from 9.1 MPa to 28.7 MPa, with the highest value achieved in a mixture of 95% concrete and 0% fibers. Water absorption rates ranged from 2.1% to 6.6%, demonstrating an effective balance between performance and durability. Environmental assessments indicated a 30% reduction in resource consumption and a 40% decrease in carbon footprint compared to traditional cobble production methods. The findings demonstrate that eco-cobbles not only meet performance standards but also offer significant environmental benefits with a 99% compliance from the results obtained by response surface methodology plots, confirming that eco-cobbles offer a viable, sustainable alternative to conventional materials, with the potential for broader application in eco-friendly construction practices.

Keywords: PET; concrete; cobble; recycling; fibers; recycling

check for updates

Citation: García-León, R.A.; Trigos-Caceres, J.; Castilla-Quintero, N.; Afanador-García, N.; Gómez-Camperos, J. Experimental and Statistical Analysis of Concrete Eco-Cobble Using Organic and Synthetic Fibers. *Processes* **2024**, *12*, 1936. https://doi.org/10.3390/pr12091936

Academic Editors: Vincent Terrasson, José Cleiton Sousa dos Santos and Maria Rios

Received: 15 July 2024
Revised: 17 August 2024
Accepted: 2 September 2024
Published: 9 September 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

1.1. Overview

The development of the construction industry in recent years has been increasing, leading to concerns among industries and construction companies about employing environmentally friendly methods. This material entails a shift in industry mentality and economic strategies, promoting the recycling and reuse of materials that could benefit construction. As a result, there is a new step towards replacing the trend of exploiting natural resources [1].

Humans have always sought skills to aid their development, and construction is no exception. Since the dawn of history, humans have sought readily available materials with long-lasting properties to provide shelter, such as stones, clay, and wood. Cement, a mixture of gypsum, limestone, and water, emerged as a pivotal material for shaping or bonding rocks for constructions, marking the inception of what would be known as Portland cement. However, cement, highly utilized in construction works, poses significant environmental concerns due to its production process. According to the BBC website, around 2.2 billion tons of CO_2 were produced in 2016, accounting for 8% of global CO_2 emissions, primarily due to cement production [2].

Today, pollution and ecological footprint are major concerns for humanity, with plastics emerging as a significant contributor to global pollution. Plastic's versatility is evident in

various everyday products, with packaging being a primary application. The production of plastic heavily relies on ethane extracted from fracking activities, and over 90% of plastics are derived from fossil fuels, posing significant environmental challenges [3]. In the United States and Europe, disposable products like packaging, food utensils, and waste bags account for about a third of plastic consumption. Moreover, plastic production processes emit approximately 850 million metric tons of pollutants from extraction, refining, and disposal in coal-fired power plants with capacities ranging from 189 to 500 Mv [4]. Since plastic production began around 1950, approximately 9.2 billion tons of plastic waste have been generated globally, with 6.3 million tons remaining unrecycled, as the environmental NGO Greenpeace reported in their publication "Colombia mejor sin plásticos" [3]. In 2016, the Colombian government stated that Colombians generate 11.6 million tons of waste annually, with only 17% being recycled. Lack of source separation and selective collection exacerbates the issue [5]. Major Colombian beverage companies heavily rely on Polyethylene terephthalate (PET) technology for packaging, contributing significantly to plastic waste [6].

On the other hand, the Colombian industry primarily utilizes only 20% of the coconut, with the rest, including husk and water, being discarded, leading to environmental problems like river and estuary pollution and landfill overflow. Approximately 35,000 L of coconut water is wasted weekly in Colombia, with husks often burnt, further harming the environment [7].

Over time, humans have introduced fibers into construction, both natural and synthetic, to enhance or modify certain material properties, aiming for efficiency and environmental benefits aligned with current regulations. Concrete cobbles, prefabricated construction elements used for pavement surfaces, undergo stringent quality control, including material characteristics, compressive strength, wear resistance, and absorption. Reusable concrete cobbles facilitate easy maintenance, offering cost advantages during pavement emergencies as they do not require demolition. Fibers in the construction industry offer various benefits, including crack control, impact resistance, fire resistance, flexural strength, and increased toughness [8]. Utilizing different fibers for reinforcement, such as steel or polymers, enhances concrete's tensile strength, flexural strength, and ductility [9]. PET elements can be recycled and added as fiber reinforcement in concrete to address pollution issues. Studies have analyzed fibers like coconut husk and PET, revealing high rigidity and toughness in coconut fibers due to their multicellular structure composed primarily of cellulose and lignin in the matrix. PET fibers also exhibit high rigidity, low toxicity, and lightweight properties. Notice that while natural fibers present an attractive option for sustainable materials, achieving consistent improvements in physical and mechanical properties and ensuring durability remains a significant challenge. Addressing these issues requires careful consideration of fiber selection, treatment processes, and composite design to balance performance with environmental and economic benefits.

Considering the above, concrete eco-cobble is an innovative material designed to enhance sustainability and performance in construction. This material incorporates eco-friendly fibers and recycled components, making it a viable alternative to traditional concrete in various applications. The development of concrete eco-cobble aligns with growing environmental concerns and the need for more sustainable building materials. Also, fibers are used to reinforce the concrete matrix, enhancing the mechanical properties and durability of the concrete cobbles.

1.2. Literature Review

The use of natural and synthetic fibers in concrete mixtures has been extensively researched, demonstrating their potential to significantly enhance various mechanical properties, making them suitable for a wide range of engineering applications. Natural fibers, such as coconut husk and palm kernel shell, offer benefits like increased tensile strength, improved resistance to cracking, and enhanced durability under environmental stressors. On the other hand, synthetic fibers like PET have been shown to improve concrete's tough-

ness, reduce permeability, and mitigate shrinkage cracking. These advancements improve concrete products' structural integrity and longevity and contribute to sustainability by utilizing waste materials. This review synthesizes key findings from recent studies, highlighting the benefits and challenges of incorporating both natural and synthetic fibers into concrete mixtures, and positions our research on eco-cobbles within this broader context of innovative material science [10].

1.2.1. Coconut Fiber in Concrete

Vidal (2019) demonstrated that incorporating coconut husk fibers in varying percentages (10%, 20%, and 30%) as substitutes for both fine and coarse aggregates significantly improved the early-age strength of concrete cobbles, surpassing conventional cobbles' resistance requirements [11]. Mundaca and Gonzales (2019) evaluated the permeability and compressive strength of pedestrian path cobbles incorporating 0.5%, 1.0%, and 1.5% coconut fibers. They found that 0.5% fiber content met the standard compressive strength requirements and significantly increased permeability, which is crucial for pedestrian applications [12]. Yerramala (2015) explored the use of fly ash and coconut shell in concrete, demonstrating that while coconut shell incorporation reduced workability compared to fly ash, it maintained a good relationship between compressive and split tensile strength [13]. Mayancela (2021) compared the effects of polypropylene, coconut husk, and glass fibers in concrete, concluding that coconut husk fibers at 0.2% provided a 13% improvement in mechanical performance over conventional pavers [14]. Quintero and González (2016) highlighted the benefits of coconut fiber's elasticity in concrete, improving toughness by preventing crack propagation [15]. Yara-Amaya (2019) showed that incorporating 20% and 30% natural fibers from coconut and fique could produce cobbles meeting standard resistance requirements. This further validates our approach of using natural fibers to achieve the desired mechanical properties in eco-cobbles [16].

1.2.2. Synthetic Fibers in Concrete

Krishnamoorthy (2007) investigated the effects of PET fibers in concrete, finding that a 1.0% volume of PET fibers with an aspect ratio of 0.45 provided optimal resistance to acid and chloride attacks, with a minimal resistance loss ratio ranging from 10.3% to 15.5% [17]. Saikia and Brito (2013) found that incorporating PET in concrete increased toughness, particularly with larger flake sizes, despite not exceeding compressive strength reference values [18]. Di Marco Morales (2015) concluded that PET incorporation improved the mechanical strength of cobbles, with 35% PET content being the most effective [19]. Ascencio et al. (2021) created 100% recycled material cobbles using PET, which exhibited favorable mechanical behavior for articulated pavements [20]. Omar and León (2017) demonstrated that PET could improve the rupture modulus of bricks, suggesting its potential as a raw material for construction applications [21]. Peñaranda and Rincón (2014) and Florez (2014) explored various percentages of plastic fibers in concrete, finding that optimal mixtures could achieve suitable mechanical properties for construction [22,23]. Tami and Landinez (2017) and Manrique (2017) analyzed the effects of PET macro fibers and coconut fiber in concrete, respectively, highlighting the need to balance fiber content for optimal mechanical performance [24,25].

1.2.3. Natural Fibers and Composite Materials in Concrete

Lainez and Villacis (2015) studied lightweight concrete with coconut waste, noting a 26% reduction in compressive strength but significant acoustic benefits, which focus on mechanical strength; the potential acoustic advantages of using coconut fibers could be an additional benefit for certain applications of eco-cobbles [26]. Ojeda (2009) demonstrated that incorporating palm kernel shells in concrete lightened the material by 35% but halved the strength compared to the control mix [27].

1.3. Aim of This Work and Scientific Contributions

This research aims to conduct an experimental study to determine the optimal percentage of PET fiber and coconut fiber incorporation, or the combined use of both, with the main objective of employing these fibers to produce cobbles for light traffic. These results will determine the mechanical properties and contribute to the cobble as a product in construction. It's worth noting that such research hasn't been conducted according to the study conducted in various bibliographic sources. Therefore, it's essential to emphasize using renewable methodologies and more environmentally friendly methods, resulting in a product that benefits the construction industry. As observed in the bibliographic references, enhancing characteristics using fibers is possible, thereby achieving sustainable social constructions.

The scientific contribution of this study lies in the following aspects: (1) The study provides an optimal mix to produce ecological concrete cobbles using organic (coconut) and synthetic (PET) fibers. This mixture has been experimentally designed and optimized to maximize the mechanical strength of the cobbles. (2) The research demonstrates the feasibility of using recycled materials like coconut and PET fibers to construct concrete cobbles. This product contributes to reducing the environmental impact associated with the production and disposal of these materials. (3) The use of statistical techniques, such as experimental design, allows optimizing the number of tests needed to evaluate the mechanical properties of the cobbles. This technique ensures efficient use of resources and provides reliable and reproducible results. And (4) The obtained results, including the compressive strength of the cobbles, are statistically validated, increasing confidence in the accuracy and relevance of the study's findings. In summary, the scientific contribution of this study lies in its innovative approach to producing ecological concrete cobbles, which utilizes recycled materials and statistical techniques to optimize the design and evaluation process.

2. Materials and Methods

2.1. Main Properties of the Materials Used

PET, such as in beverage bottles, is commonly found in our daily lives. PET possesses characteristics such as being lightweight, mechanical resistance to compression, and recyclability. Additionally, it exhibits high transparency and glossiness [28]. The main physical and mechanical PET properties can be obtained from [21]. Also, coconut fiber contains substances such as tannin and lignin, which provide cellulose with rigidity, impermeability, durability, and resistance against biological agents. The most important physical, chemical, and mechanical properties of the coconut fibers can be obtained from [29].

The experimental investigations focused on understanding the mechanical behavior of mortar mixed with various fibers, including cellulose fibers derived from paper sludge, PET fibers, and other natural fibers such as sisal and jute. The traditional mortar mix can be used as a control mix, while other mixtures incorporate 1% and 2% cellulose fibers, 1% PET fibers, and 1% other natural fibers. The key components for all mixtures included cement (1000 kg/m^3), sand (2000 kg/m^3), and water (500 kg/m^3), maintaining a consistent water-to-cement ratio of 0.5.

2.2. Fiber Properties and Impact

With a tensile strength of 300–500 MPa and Young's modulus (E) of 10–30 GPa, cellulose fibers significantly altered the post-crack behavior of mortar. Increasing the fiber content improved the material's deformation capacity due to the fibers' energy absorption and tensile stress transfer capabilities [30]. Known for their tensile strength of 500–700 MPa and E of 4–7 GPa, PET fibers enhanced flexural tensile strength but showed mixed results for compressive strength depending on fiber dispersion [31]. In the case of sisal and jute fibers, values can differ widely in tensile strength (200–800 MPa) and E (10–80 GPa), improving flexural properties but could negatively impact compressive strength if not uniformly dispersed [32].

Adding cellulose fibers (1% and 2%) to mortar improved its flexural strength and post-crack deformation but reduced compressive strength due to increased porosity. Mortars

with PET fibers showed enhanced flexural strength at 1% content, but higher percentages led to non-uniform fiber dispersion and reduced performance. The impact of other natural fibers followed a similar trend, with benefits in tensile strength but potential drawbacks in compressive strength due to inconsistent fiber distribution [33]. Overall, while the eco-friendly mortars slightly increased the compressive strength of masonry walls, the primary benefits were observed in flexural performance and crack control, highlighting the importance of uniform fiber dispersion in achieving optimal results. These findings underscore the dual objective of promoting sustainable materials while maintaining adequate mechanical performance in construction applications.

2.3. Technical Standards Used

The coarse and fine materials were obtained from the crusher "Concretos y triturados algodonal SAS" with which the characterization of their physical and mechanical properties is carried out, considering the standards INV E-202 (Sample Reduction of Aggregates by Quartering), INV E-213 (Sieve Analysis of Fine and Coarse Aggregates), INV E-217 (Bulk Density (Unit Weight) and Voids in Aggregate), INV E-218 (Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine), INV E-222 (Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate) and INV E-223 (Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate) which can obtained from [34].

2.4. Experimental Design

With the aid of the Statgraphics program, a mixture design composed of three components was obtained: concrete, coconut fiber, and PET fiber, which are the main elements of the eco-cobblestones. The conventional cobblestone, consisting of 100% concrete, is taken as a reference point, with fibers being added to vary the mixture by up to 10%. The experiments were randomized to account for hidden variables, ensuring the robustness of the results. Additionally, a quadratic model was selected to fit first- and second-order terms, allowing for a comprehensive analysis of the interactions between the components. The percentages of materials in the mixture were limited as follows:

- Concrete: 90% (low) to 100% (high), with a 10% variation (Δ%).
- Coconut Fiber: 0% (low) to 10% (high).
- PET Fiber: 0% (low) to 10% (high).

Considering the above, the following points were considered to develop the mixes:

- ➢ Fiber Type and Dosage: The design mixes were selected to evaluate the effects of different types and amounts of fibers on the performance of the eco-cobble. Various fiber dosages were tested, ranging from 0% to 10% for both coconut and PET fibers, to assess their influence on strength, durability, and workability. This approach allowed us to identify the optimal mix that balances mechanical performance and sustainability.
- ➢ Comparative Analysis: The mixes were selected to provide a comparative analysis between different fiber combinations. This selection enabled a direct comparison between the effects of PET fibers (synthetic) and coconut fibers (natural) on the material's properties, offering insights into the advantages and limitations of each fiber type.
- ➢ Consistency in Testing: Some design mixes are repeated to ensure testing consistency and verify the reproducibility of results. Repeated testing of specific mixes helps confirm the reliability of the data and identify any variability that might occur during the experimentation process.
- ➢ Quality Control: Repeating mixes also serves as a quality control measure to ensure that the results are robust and not affected by anomalies in the preparation or testing procedures. This repetition helps validate the experimental results and refine the conclusions drawn from the data.

➢ Incremental Analysis: Repeating certain mixes with slight variations allows for a detailed comparative evaluation of how different fiber content affects the performance metrics. This point is particularly useful for analyzing the incremental impact of adding or altering fiber types in the mixture.

Table 1 shows the experimental design proposed for executing the dosages to obtain the cobbles for experimental tests. Note that some dosages are replicated because the statistical software (Statgraphics version 19) optimizes the combinations to reduce the test amount, as presented in Table 2. This experimental design is part of the initial observation and previous works, ensuring that the study's findings are grounded in a robust methodological framework. By systematically varying the proportions of concrete, coconut fiber, and PET fiber, it was possible to develop eco-cobbles with enhanced mechanical properties and environmental sustainability.

Table 1. Experimental Design with 3 Different Materials: Concrete, Coconut Fiber, and PET Fiber.

Mixture	Concrete (%)	F. Coconut (%)	F. PET (%)
1	95.0	5.0	0.0
2	100.0	0.0	0.0
3	95.0	0.0	5.0
4	91.667	1.667	6.667
5	93.333	3.333	3.333
6	90.0	5.0	5.0
7	90.0	0.0	10.0
8	96.667	1.667	1.667
9	90.0	10.0	0.0
10	91.667	6.667	1.667
11	100.0	0.0	0.0
12	90.0	10.0	0.0
13	90.0	0.0	10.0
14	95.0	5.0	0.0
15	95.0	0.0	5.0
16	90.0	5.0	5.0
17	93.333	3.333	3.333
18	100.0	0.0	0.0
19	90.0	10.0	0.0
20	90.0	0.0	10.0

Taking into account the experimental design in Statgraphics, ten (10) different types of mixtures were obtained with the percentage dosage of the three established materials (concrete, coconut fiber, and PET fiber) [35]. Additionally, some dosages were replicated at least three times to guarantee the statistical results. For this research work, three physical-mechanical tests will be performed on the cobbles: absorption, flexural strength, and compressive strength; thus, a total of 120 samples (cobbles) will need to be elaborated. Table 2 shows the calculations to obtain the number of cobbles necessary to execute according to the ages to be evaluated, which were considered at 14 and 28 days.

Table 2. Quantity of paving cobble by established dosages in Kg%.

Mixture	Dosage (Kg%)	Cobble Number	Test Amount	14 Days	28 Days
1	95 + 5 + 0	2	3	6	6
2	100 + 0 + 0	3	3	9	9
3	95 + 0 + 5	2	3	6	6
4	91.6 + 1.6 + 6.6	1	3	3	3

Table 2. *Cont.*

Mixture	Dosage (Kg%)	Cobble Number	Test Amount	14 Days	28 Days
5	93.3 + 3.3 + 3.3	2	3	6	6
6	90 + 5 + 5	2	3	6	6
7	90 + 0 + 10	3	3	9	9
8	96.6 + 1.6 + 1.6	1	3	3	3
9	90 + 10 + 0	3	3	9	9
10	91.6 + 6.6 + 1.6	1	3	3	3
-	-	-	Total	60	60

The NTC-2017 standard [36] was considered to determine the geometry of the cobbles, bearing in mind that the thickness of the cobbles should not exceed 5. Based on this information, cobbles with the following dimensions will be chosen: a length of 200 mm, a width of 100 mm, and a thickness of 80 mm. For pavements, general use for light traffic, sidewalks, and parking lots will be defined, with an average weight of ~3.5 kg and a compressive strength of 3000 Psi [37] for a concrete dosage 1:2:3 (22 MPa).

2.5. Granulometric Analysis of Coarse and Fine Aggregates (INV E-213)

Through this standard, the distribution of sizes of coarse and fine aggregates was quantified. The sieve system specified by the standard was used (See Figure 1) [34].



Figure 1. Sieves used for granulometric analysis of aggregates.

The following steps were followed for the granulometric analysis of the coarse aggregate:

1. The sieves with openings of 1 ½″, 1″, 3/4″, 1/2″, 3/8″, No. 4, and bottom are used to separate the coarse aggregate.
2. Then, the retained weights on each sieve are obtained, which is the amount of material in grams retained on each sieve.
3. The retained percentage is calculated using Equation (1), which indicates that the retained weight of each sieve should be divided by the total weight of the sample. For the sample under study, a weight of 6010.6 gr was used. Below is the step-by-step calculation for the retained percentage for the 1 ½″ and 1″ sieves.

$$\% \text{ Retained sieve} = \frac{\text{Retained weight}}{\text{Total weight of the sample}} \times 100 \quad (1)$$

$$\% \text{ Retained sieve } 1\ 1/2'' = \frac{0 \text{ gr}}{6010.6 \text{ gr}} \times 100 = 0$$

$$\% \text{ Retained sieve } 1'' = \frac{86.5 \text{ gr}}{6010.6 \text{ gr}} \times 100 = 1.44$$

4. The accumulated withheld percentage is the sum of the previous withheld percentages.

$$\%\ \text{Accumulated sieve retention} 1\ ^1/_2'' = 0$$

$$\%\ \text{Accumulated sieve retention}\ 1'' = 0 + 1.44 = 1.44$$

5. The percentage that passes (% Pass) subtracts 100% minus each accumulated percentage withheld.

$$\%\ \text{Passes}\ 1\ ^1/_2'' = 100 - 0 = 100$$

$$\%\ \text{Accumulated sieve retention}\ 1'' = 100 - 1.44 = 98.56$$

The procedures described above must be calculated for each of the sieves used. Below is the procedure for Granulometry for fine aggregate:

1. The use of sieves with openings of $3/4''$, $1/2''$, $3/8''$, No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, No. 200, and background is used for fine aggregate.
2. Afterward, the weight retained in each sieve is obtained. This weight is the amount of grams of material retained in each sieve.
3. The percentage retained is calculated by dividing the retained weight of each sieve by the total weight of the sample, with a total weight of 1556.2 gr. Then, Equation (1) is used again.

$$\%\ \text{Retained sieve} = \frac{14.2\ \text{gr}}{1556.2\ \text{gr}} \times 100 = 0.91$$

$$\%\ \text{Retained sieve} = \frac{23.9\ \text{gr}}{1556.2\ \text{gr}} \times 100 = 1.54$$

4. The accumulated withheld percentage is the sum of the previous withheld percentages.

$$\%\ \text{Accumulated sieve retention}\ 3/4'' = 0.91$$

$$\%\ \text{Accumulated sieve retention}\ 1/2'' = 0.91 + 1.54 = 2.45$$

5. The percentage that passes is the subtraction of 100% minus each accumulated percentage withheld.

$$\%\ \text{Passes}\ 3/4'' = 100 - 0.91 = 99.09$$

$$\%\ \text{Accumulated sieve retention}\ 1/2'' = 100 - 2.45 = 97.55$$

On the other hand, the aggregates' physical properties were calculated, as shown in Table 3. Note that the volume of the laboratory cylinder is equal to $\pi \times (0.165\ \text{m}/2)^2 \times 0.165\ \text{m} = 0.0035\ \text{m}^3$, and equations were obtained from [34].

Table 3. Main physical properties of the aggregates.

Property	Equation	Equation No.	Result	
			Fine	Coarse
Density	$\text{Average unit mass} = \frac{\sum(\text{unit masses by tamping 1, 2 and 3})}{3}$	(2)	1281.234 kg/m^3	
Degradation resistance	$\%\ \text{Loss} = \frac{\text{Initial sample weight} - \text{Final sample weight}}{\text{Initial sample weight}} \times 100$	(3)	9.04%	
Relative density	$\text{Density} = \frac{\text{Oven dry sample mass}}{(\text{Pycnometer mass} + \text{destilled water})}$	(4)	1.227	1.4528
Apparent density	$\text{Density} = \frac{997.5 \times \text{Oven dry sample mass}}{(\text{Pycnometer mass} + \text{destilled water})}$	(5)	1548.484	1456.653
Absorption	$\text{Absortion} = \frac{\text{Surface dry sample mass} - \text{Oven dry sample mass}}{\text{Oven dry sample mass}} \times 100$	(6)	17.046	1127

2.6. Cobble Development

The specifications of the NTC-2017 standard were considered for the dimensions of the cobbles. Wooden molds were made, each with a capacity of 5 cobbles, designed with screws to facilitate the demolding process. The PET fiber was cut from water bottles, which were sanded to provide roughness on their surface because PET has poor adhesion to concrete. The PET sheets' dimensions were cut into 2 × 50 mm dimensions to distribute them better in the mixture. The coconut fiber was obtained from a company in Medellin, Colombia, that specializes in distributing this coconut husk, which undergoes a treatment after harvesting. It is submerged for about nine months to eliminate salts and improve its properties. This treatment was performed because it is used in agriculture as a base for specialized fertilizers to enhance soil structure.

The mixture of synthetic and organic fibers (PET and coconut fiber) with concrete is shown in Figure 2. Considering the previously established experimental design, it is important to note that each mixture contained a different dosage. Additionally, Figure 3 depicts the curing process of the pre-formed cobbles. Note that the mixtures were prepared according to fiber addition percentages, with 20 cobbles made daily and de-molded after 24 h.



Figure 2. (**a**) Mixture with adding coconut fiber and PET fiber, (**b**) Homogenization, and (**c**) Pouring onto the molds.

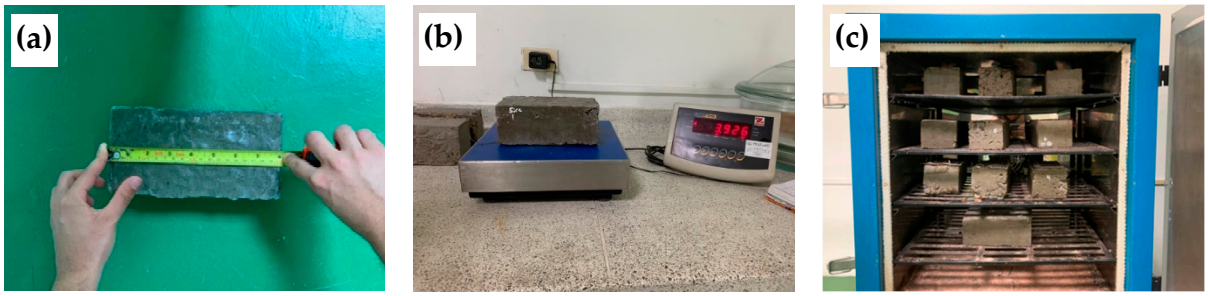


Figure 3. (**a**) Measurement taking, (**b**) weight of the cobbles before testing, and (**c**) oven drying.

After the respective time for testing the cobbles at 14 and 28 days, groups were considered based on the proposed experimental design, distributed across flexural, compression, and absorption tests. Before the tests, it was necessary to take measurements (morphology) of each cobble before they were tested in the respective laboratory tests, as shown in Figure 3a. For the absorption tests after 24 h of curing in water immersion, the cobbles were weighed, considering an apparent or superficial drying, which involves removing the water from the surface without exposing it to outdoor or oven drying. Then, the weight of the submerged cobbles is measured, as shown in Figure 3b, to calculate the absorption percentage. Finally, the cobbles are placed in the oven for a period of 24 h to obtain their dry weight (see Figure 3c).

2.7. Mechanical Tests

Visually, it was observed that the cobbles with the addition of coconut at any percentage showed less failure during both compression and flexural testing compared to cobbles containing only PET or 100% concrete, as depicted in Figure 4. Figure 4a shows the cobble with 100% concrete, while Figure 4b displays a cobble with a 5% addition of coconut fiber. It can be observed that the crack or failure amplitude is smaller in the cobble containing the organic fiber.

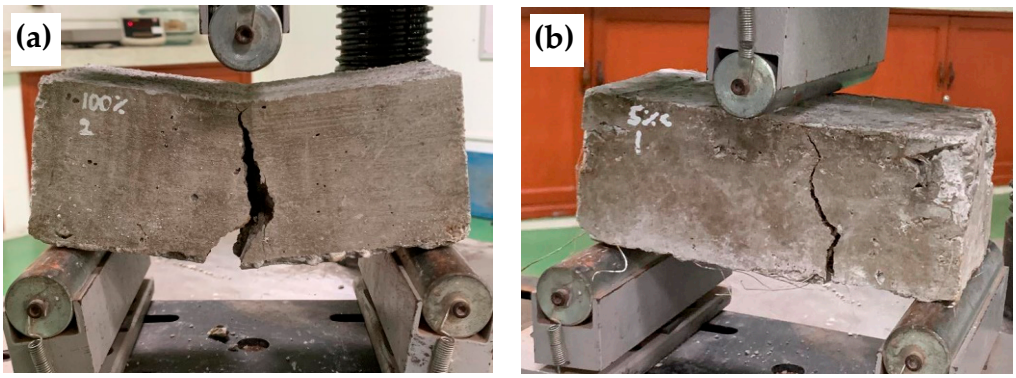


Figure 4. Cobbles tested under tension test. (**a**) failure mode 1, and (**b**) failure mode 2.

The cobbles tested under compression are depicted in Figure 5. The cobble in Figure 5a is made of 100% concrete, while the cobble in Figure 5b contains a 5% addition of coconut fiber. It can be observed that while the 100% concrete cobble deteriorates more rapidly, the 5% coconut fiber cobble exhibits less amplitude in the failure compared to the 100% concrete cobble.

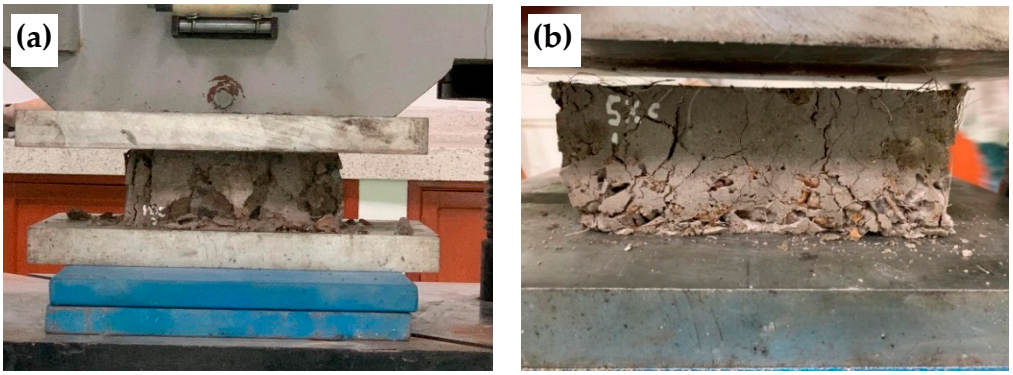


Figure 5. Cobbles tested under compression test. (**a**) failure mode 1, and (**b**) failure mode 2.

As shown in Figure 6, cobbles with any incorporation of coconut fiber exhibit less pronounced cracks upon failure compared to conventional cobbles. Additionally, it can be observed that the cobbles maintain more of their original shape when coconut fiber is incorporated, as depicted in Figure 6a, where a cobble with 6.6% coconut fiber and 1.6% PET is shown, and in Figure 6b, where a cobble with 10% coconut fiber is shown. Despite being subjected to compression tests, the cobbles are not destroyed or do not exhibit more pronounced failures than the conventional 100% concrete cobble or a cobble containing only PET.

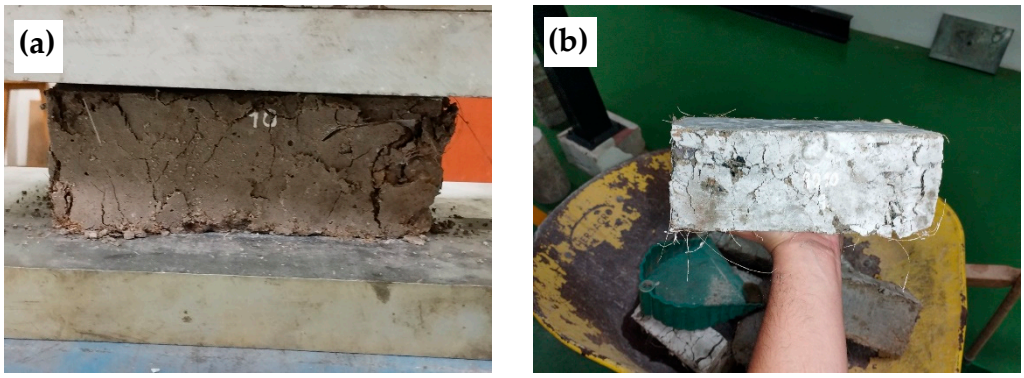


Figure 6. Cobbles with coconut fiber addition (**a**) 6.6%, and (**b**) 10%.

2.8. Statistical Analysis

Using the Statgraphics software, a mixture design experiment was created employing the Simplex-Centroid method to define a quadratic model, with percentages of fiber addition to the mixture being constrained and randomized. Then, the design is expanded to protect against hidden variable effects. As a result, 10 dosages were obtained with repetitions to manipulate variables (see Table 2).

Descriptive statistics, including mean values, standard deviations, and ranges, were calculated for each mixture to summarize the central tendencies and variability in the mechanical properties. In this way, ANOVA (analysis of variance) was used to evaluate the differences in mechanical properties across the various fiber mixes, determining if there were statistically significant differences between groups. Also, regression analysis was applied to explore relationships between fiber dosage and mechanical properties, helping to identify potential correlations and trends.

On the other hand, Response Surface Methodology (RSM) was employed to optimize the mix design and understand the interactions between different variables (i.e., PET and coconut fiber dosages) on the mechanical properties of the eco-cobble. The methodology involves:

- Design of Experiments: A central composite design (CCD) was used to systematically vary the levels of PET and coconut fibers in the mixtures. This design allows for the evaluation of quadratic effects and interaction effects between the variables.
- Model Fitting: The collected data were fitted to a second-order polynomial model to create response surfaces. This model aids in visualizing how changes in fiber dosages affect the mechanical properties and in identifying optimal conditions for desired performance.
- Optimization: RSM was used to identify the optimal combination of PET and coconut fiber dosages that maximize the desired properties (e.g., compressive strength, flexural strength) while minimizing undesirable attributes (e.g., water absorption); this analysis is based on predictive equations.

3. Results and Discussions

For the mixture design, it was necessary to study and analyze the samples of coarse and fine aggregates. By conducting the sieve analysis following the guidelines of standard INV E-213, a fineness modulus of 4.074 was obtained. This value is calculated from the gradation of the fine aggregate and serves as an index to determine the characteristics of the aggregates. The fineness modulus is obtained by dividing 100 by the sum of the cumulative percentages retained on each sieve. It is closely related to the grain size of the aggregate: the larger the grain size, the higher its value, and vice versa. According to specifications, the value of the fineness modulus should not be less than 2.3 or greater than 3.1 [38]. Considering this, a starting dosage 1:2:3 (22 MPa) for the concrete was selected to continue the experimental process. Additionally, a percentage of variation was established for the combination of fibers and concrete. Based on previous research, including articles and theses, a percentage of 10% was selected based on the results obtained by [39].

3.1. Mechanical Test Results

Table 4 summarizes all laboratory tests (compression, flexure, and absorption) conducted on the cobbles at various dosages.

Table 4. Compression, Flexure, and Absorption Test Results on Cobbles at Different Dosages.

Mixture	Concrete (%)	F. Coconut (%)	F. PET (%)	Compression Resistance				Flexural Strength				Absorption (%)
				14 Days (MPa)	Max. Load. (Psi)	28 Days (MPa)	Max. Load. (Psi)	14 Days (MPa)	Max. Load. (Psi)	28 Days (MPa)	Max. Load. (Psi)	
1	95	5	0	16.6	339.7	14.9	311.5	7.6	19.9	1.4	8.1	5.75
2	100	0	0	19.3	386.5	14.5	303.9	2.8	6.9	3.4	19.8	6.22
3	95	0	5	26.8	561.7	17.2	361.1	2.4	19.9	3.7	20.7	4.07
4	92	2	7	14.7	301.5	16.3	344.0	2.5	7.0	3.2	19.0	4.93
5	93	3	3	17.2	363.6	19.7	414.1	3.0	8.4	3.5	18.2	4.36
6	90	5	5	14.1	297.7	9.10	187.6	6.3	17.0	3.2	17.5	5.34
7	90	0	10	15.1	318.0	19.1	392.7	2.1	17.7	2.9	18.4	3.50
8	97	2	2	12.4	255.0	13.0	270.5	6.6	17.1	3.2	17.8	5.73
9	90	10	0	15.1	310.3	19.8	414.0	6.5	17.3	3.5	18.0	6.05
10	92	7	2	20.6	412.7	19.9	415.8	5.7	15.4	3.2	19.0	5.65
11	100	0	0	18.9	379.5	14.5	307.1	6.4	16.1	3.4	18.8	5.90
12	90	10	0	14.1	295.0	21.1	442.9	5.7	15.4	3.1	17.1	6.25
13	90	0	10	11.9	249.2	19.0	389.5	2.2	17.4	3.2	19.0	3.28
14	95	5	0	11.5	235.0	20.3	423.7	6.5	17.6	3.6	21.0	5.54
15	95	0	5	21.1	440.1	28.7	598.9	1.4	12.0	3.6	21.0	4.39
16	90	5	5	16.7	348.8	12.5	267.2	5.7	17.4	3.4	19.6	5.06
17	93	3	3	15.6	327.0	20.1	413.4	6.4	18.6	3.1	17.5	4.68
18	100	0	0	19.0	391.0	15.2	316.3	6.0	14.8	3.6	20.2	6.06
19	90	10	0	12.8	259.8	13.0	273.5	5.5	16.3	3.1	19.4	6.15
20	90	0	10	13.9	284.9	13.6	280.0	2.6	20.1	3.2	18.5	3.39

Note: Results of tests conducted on compression, flexure, and absorption at ages of 14 and 28 days.

The eco-cobble mixtures with PET fiber demonstrated superior compression strength compared to conventional concrete, achieving compressive strengths of 26.8 MPa at 14 days and 28.7 MPa at 28 days, exceeding the typical strength of conventional concrete around 22 MPa. This improvement highlights PET fiber's effectiveness in enhancing the compressive properties of concrete. However, while the coconut fiber addition improved crack resistance in the eco-cobble mixtures, the overall flexural strength decreased over time, dropping significantly from 6.6 MPa at 14 days to 3.2 MPa at 28 days. Conventional concrete usually maintains more consistent flexural strength over time. Other eco-cobble mixtures, such as those with alternative recycled materials, may offer varied performance but generally aim to balance flexural strength and environmental benefits.

The eco-cobble mixtures with coconut fiber showed higher water absorption rates, with the highest observed in the mixture with 10% coconut fiber, which is higher than typical absorption rates for conventional concrete. PET fiber mixtures, on the other hand, exhibited lower absorption rates, suggesting better water resistance compared to other eco-cobble options and conventional concrete. Also, compared to other eco-cobble mixtures, such as those using different natural or recycled fibers, the PET fiber mixtures in this study achieved higher compressive strength, aligning well with sustainable construction goals [40]. Coconut fiber mixtures offered better crack resistance but showed decreased long-term flexural strength, which could be improved with additional optimization. Other eco-cobble mixtures may provide different performance characteristics based on their specific compositions and environmental considerations.

Figure 7 depicts graphical representations of compression tests performed on the cobbles at 14 and 28 days, respectively, for the entire experimental set. As was observed,

the dosage yielding the highest compression was 95% concrete, 0% coconut fiber, and 5% PET (mixture 3). At 14 days, mixture 3 achieved values of 26.86 MPa and 21.15 MPa, while at 28 days, these values were 17.19 MPa and 28.78 MPa (See Figure 7a).

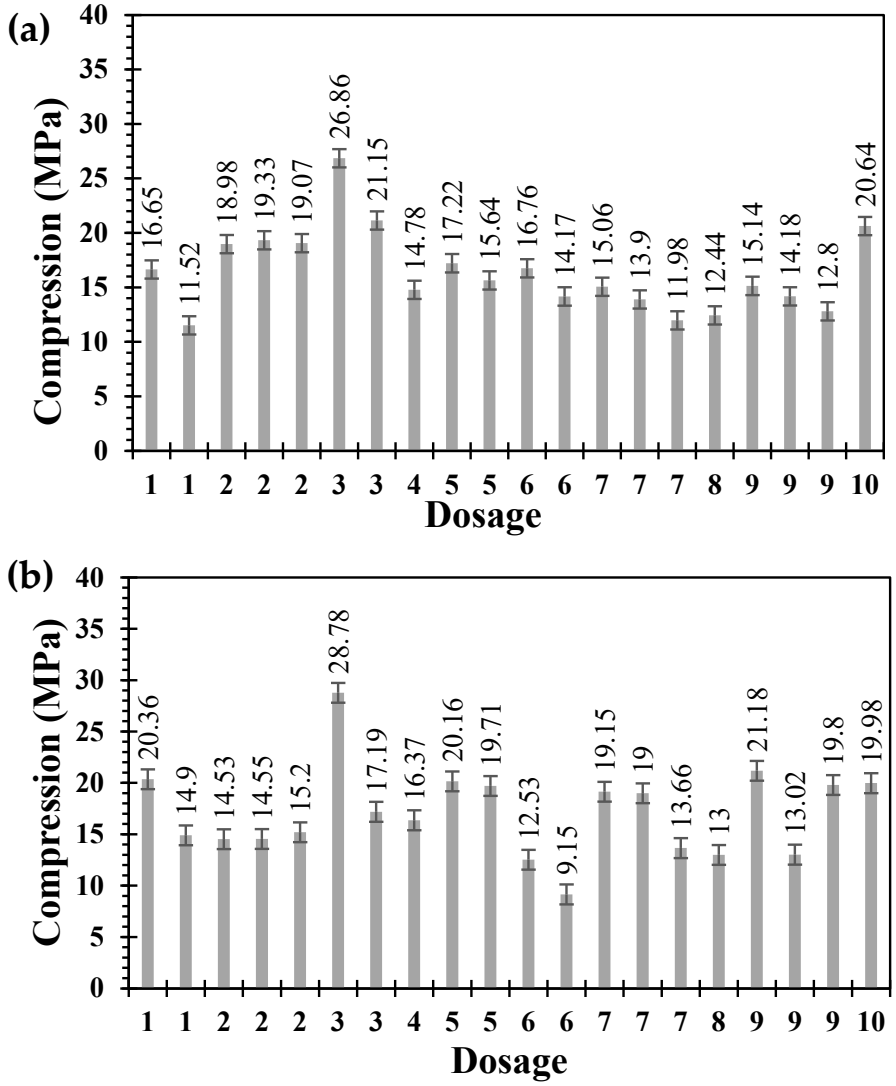


Figure 7. Compression results at (**a**) 14 days and (**b**) 28 days.

As shown in Figure 7b, at 28 days, one of the samples exhibited a 40% reduction compared to the 14 days. This phenomenon is attributed to different factors associated with the manufacturing process. However, it is noteworthy that one of the samples showed a considerable increase at 28 days (10%), surpassing the samples consisting of 100% concrete (mixture 2), which achieved compression results at 14 days of 19.33 MPa, 18.98 MPa, and 19.07 MPa, and at 28 days of 14.53 MPa, 14.55 MPa, and 15.2 MPa. The compression strength of mixture 3 exceeded that of mixture 2, which serves as the reference (100% concrete). The dosage with 7% coconut fiber and 2% PET fiber (mixture 10), which exhibited the highest compression strengths, showed no significant decrease at either 14 or 28 days, suggesting minimal variation with age differences.

Figure 8 presents graphical representations of the tensile test results conducted on the cobbles at 14 and 28 days, respectively, for the entire experimental set. The dosage yielding the highest tensile strength was the mixture with a 5% addition of coconut fiber (mixture 1), exhibiting values at 14 days of 7.65 MPa–6.51 MPa and 28 days of 1.45 MPa–3.65 MPa. Additionally, it was observed that dosages containing coconut fiber showed high tensile strength at 14 days, but a considerable decrease in strength of approximately 50% was noted at 28 days. Among the

properties of coconut fiber, it is evident that it retains moisture. Thus, it was concluded that this is a key factor influencing the decrease in tensile strength values. Moreover, coconut fibers do not allow for proper distribution of other aggregates within the mixture.

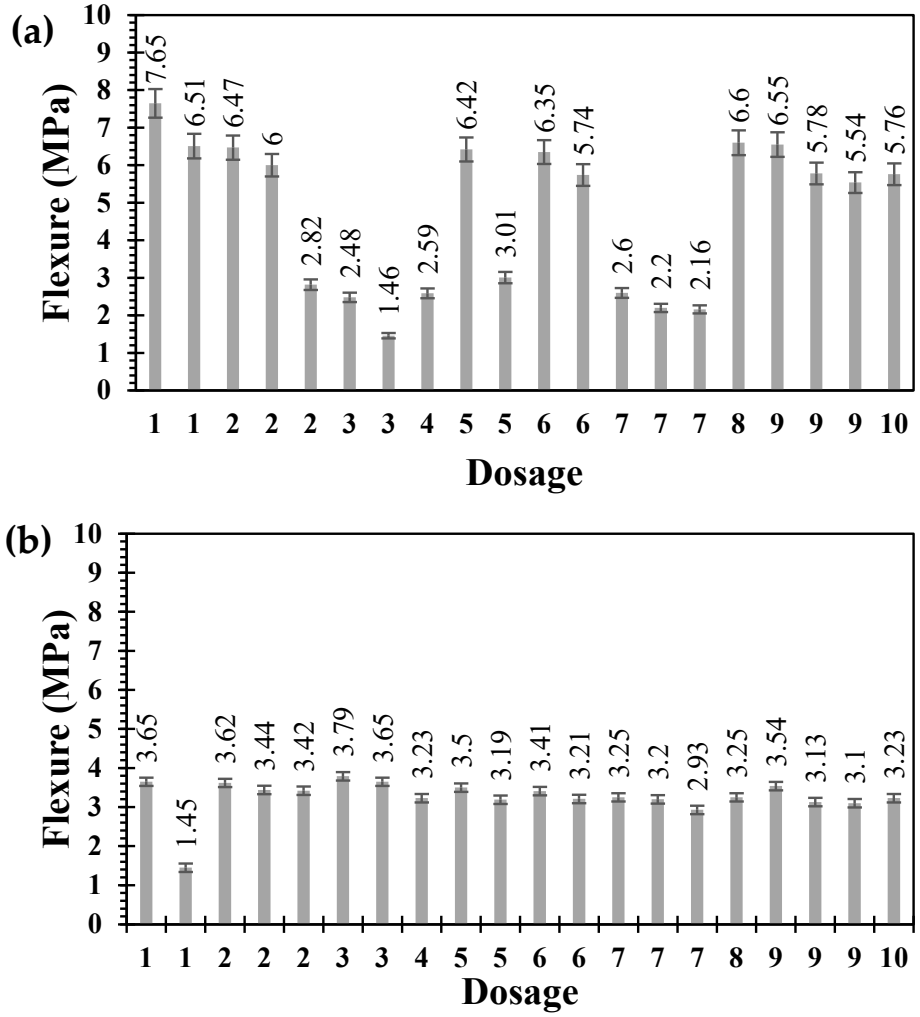


Figure 8. Tensile Test Results at (**a**) 14 days and (**b**) 28 days.

Fibers in the construction industry offer various benefits, including crack control, impact resistance, fire resistance, flexural strength, and increased toughness. Mechanical tests assessed the influence of varying fiber proportions and different preparation methods, aiming to develop sustainable materials with adequate mechanical performance. Natural fibers can alter post-crack behavior, with mortars containing fibers continuing to deform after reaching peak load, unlike traditional mortars exhibiting a sudden load decrease. This behavior is due to the energy absorbed by the fibers and their ability to transfer tensile stresses across cracks, enhancing deformation capacity. Mortars with well-dispersed fibers showed low variations in flexural tensile strength but a 10% decrease in compressive strength due to increased porosity (depending on the fiber kind). Mortars prepared without rigorous control displayed increased flexural strength with 1% fiber content due to the fiber bridging effect, but higher contents led to strength reductions [41].

Figure 9 depicts a graphical representation of the absorption test results conducted on the cobbles for the entire experimental set. The dosage yielding the highest absorption value was the mixture with a 10% addition of coconut fiber (mixture 9), presenting a value of 6.25 MPa. The lowest absorption values were found in mixture 7 with a 10% addition of PET and 0% coconut fiber. Furthermore, it is observed that dosages containing PET have lower values compared to mixtures containing coconut fiber (mixtures 1, 4, 5, 6, 8, 9,

and 10). It is worth noting that according to the consulted literature in various databases, the absorption test was not commonly employed. Considering the NTC-2017 standard, it is recommended that cobbles do not exceed an absorption value of 8%. None of the laboratory tests conducted on any of the mixtures exceeded the 8% threshold.

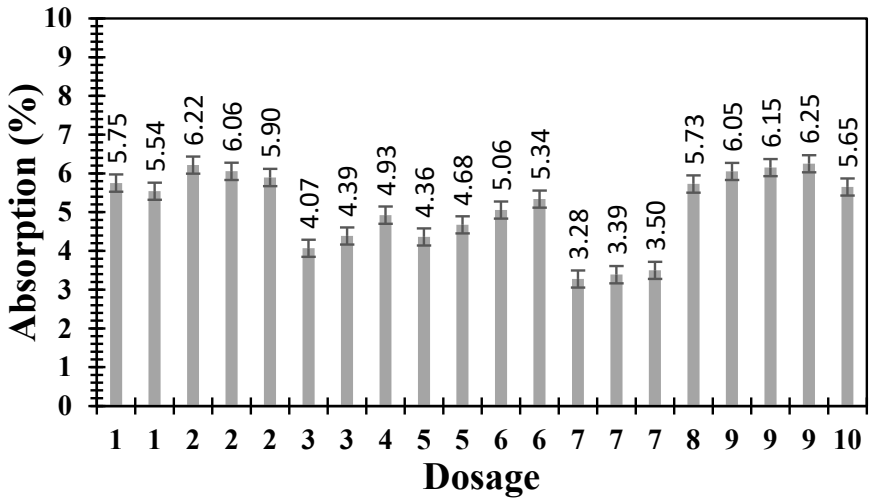


Figure 9. Absorption test results.

3.2. Statistical Analysis Results

The sum of the squares column represents a measure of variation or deviation from the mean. The degrees of freedom (DOF) indicate the amount of information in the data used to estimate the value of an unknown population parameter, considering the variability of these estimates. The value is determined based on the number of observations in the sample and the number of parameters in the model. The mean square estimates the population variance by dividing the corresponding sum of squares by the degrees of freedom. The F-ratio represents the ratio between two variances, while the *p* value measures the probability of evidence against the null hypothesis. Smaller *p* values provide stronger evidence against the null hypothesis. It's worth noting that a *p* value is considered significant when it is less than 0.05. This behavior means there's only a 5% risk that the data does not follow a normal distribution [42].

Table 5 displays the results of data analysis for a special linear, quadratic, and cubic model for compression and flexure at 14 and 28 days, respectively, as well as the absorption test.

Table 5. Estimated Effects of the Full Model for Compression, Tension, and Absorption.

Test		Source	Sum of Squares	Gl	Middle Square	F-Ratio	*p*-Value
COMPRESSION (MPa)	14 days	Half	5388.06	1	5388.06	-	-
		Linear	54.64	2	27.32	2.18	0.1438
		Quadratic	83.21	3	27.73	2.99	0.0672
		Special Cubic	8.31	1	8.31	0.89	0.3634
		Error	121.74	13	9.36	-	-
		Total	5655.97	20	-	-	-
	28 days	Half	5855.73	1	5855.73	-	-
		Linear	0.78	2	0.39	0.02	0.9813
		Quadratic	149.62	3	49.87	3.42	0.0471
		Special Cubic	4.68	1	4.68	0.30	0.5902
		Error	199.65	13	15.36	-	-
		Total	6210.47	20	-	-	-

Table 5. *Cont.*

Test		Source	Sum of Squares	Gl	Middle Square	F-Ratio	*p*-Value
FLEXURE (MPa)	14 days	Half	448.31	1	448.31	-	-
		Linear	42.49	2	21.24	10.48	0.0011
		Quadratic	14.18	3	4.73	3.27	0.0532
		Special Cubic	0.24	1	0.25	0.16	0.6935
		Error	20.01	13	1.54	-	-
		Total	525.25	20	-	-	-
	28 days	Half	199.27	1	199.27	-	-
		Linear	0.44	2	0.22	0.60	0.5616
		Quadratic	5.21	3	1.74	21.45	0.0000
		Special Cubic	0.60	1	0.60	14.70	0.0021
		Error	0.53	13	0.04	-	-
		Total	206.06	20	-	-	-
ABSORPTION (%)		Half	523.26	1	523.26	-	
		Linear	16.08	2	8.04	53.76	0.0000
		Quadratic	1.17	3	0.39	4.00	0.0298
		Special Cubic	0.05	1	0.05	0.57	0.4648
		Error	1.31	13	0.10	-	-
		Total	541.89	20	-	-	-

3.2.1. ANOVA for the Analyzed Variables

In Table 6, the results of the analysis of variance (ANOVA) for compression and flexure at 14 and 28 days, as well as for absorption, are presented. Additionally, it was observed that the *p* value is less than 0.05 at 14 days, meaning that this value represents only a 5% risk that the data does not follow a normal distribution [42]. Conversely, for the values at 28 days, due to the test's nature and the samples' curing time, adjusted and/or constant values are not obtained as the curing time of the samples increases [43].

Table 6. ANOVA for Compression, Flexure, and Absorption at 14 and 28 Days.

Test		Source	Sum of Squares	Gl	Middle Square	F-Ratio	*p*-Value
COMPRESSION (MPa)	14	Quadratic Model	137.85	5	27.57	2.97	0.0495
		Total error	130.05	14	9.28	-	-
		Total (corr.)	267.91	19	-	-	-
	28	Quadratic Model	150.41	5	30.08	2.06	0.1316
		Total error	204.33	14	14.59	-	-
		Total (corr.)	354.74	19	-	-	-
FLEXURE (MPa)	14	Quadratic Model	56.68	5	11.33	7.830	0.0011
		Total error	20.26	14	1.44	-	-
		Total (corr.)	76.94	19	-	-	-
	28	Quadratic Model	5.65	5	1.13	13.97	0.0001
		Total error	1.13	14	0.08	-	-
		Total (corr.)	6.79	19	-	-	-
ABSORPTION (%)		Quadratic Model	17.25	5	3.45	35.31	0.0000
		Total error	1.36	14	0.09	-	-
		Total (corr.)	18.62	19	-	-	-

3.2.2. Quadratic of Results for Model Adjustment

Table 7 summarizes the results of the experimental data for the optimal sample. In this table, variable (A) represents concrete, variable (B) represents coconut fiber, and variable (C) represents PET fiber. Below these variables, the combinations are shown: AB for concrete with coconut fiber, AC for concrete with PET, and BC incorporating both coconut and PET

fibers in the concrete mixture. Considering this, the optimal combination for compression and flexure at 14 and 28 days is determined to identify the combination that yields a *p* value less than 0.05, bearing in mind that this value represents only a 5% risk that the data does not follow a normal distribution [42]. Ultimately, it was found that the AC combination is the most suitable for compression at both 14 and 28 days and similarly for flexure at 14 days, although the *p* value for the latter was not less than 0.05. It was selected because its value was not significantly distant from the ideal value (0.05), which stands at 0.0636.

Table 7. Quadratic Results for Model Fitting of Compression, Flexure, and Absorption at 14 and 28 Days.

Test		Parameter	Error		Statistics	
			Estimated	Standard	T	*p*-Value
COMPRESSION	14 days	A	18.63	1.73	-	-
		B	14.84	1.73	-	-
		C	13.53	1.73	-	-
		AB	−13.18	9.08	−1.45	0.1687
		AC	23.60	9.08	2.59	0.0210
		BC	4.80	9.08	0.52	0.6054
	28 days	A	14.10	2.17	-	-
		B	18.35	2.17	-	-
		C	17.10	2.17	-	-
		AB	7.17	11.38	0.63	0.5387
		AC	27.96	11.38	2.45	0.0277
		BC	−23.05	11.38	−2.02	0.0624
FLEXURE	14 days	A	5.29	0.68	-	-
		B	5.90	0.68	-	-
		C	2.24	0.68	-	-
		AB	6.04	3.58	1.68	0.1139
		AC	−7.22	3.58	−2.01	0.0636
		BC	6.34	3.58	1.76	0.0985
	28 days	A	3.47	0.16	-	-
		B	3.26	0.16	-	-
		C	3.06	0.16	-	-
		AB	−6.25	0.84	−7.36	0.0000
		AC	2.52	0.84	2.97	0.0100
		BC	1.43	0.84	1.69	0.1119
ABSORPTION		A	6.09	0.17	-	-
		B	6.14	0.17	-	-
		C	3.45	0.17	-	-
		AB	−2.07	0.93	−2.22	0.0432
		AC	−1.93	0.93	−2.07	0.0564
		BC	1.58	0.93	1.70	0.1110

Note: A: Concrete. B: F. Coconut. C: F.PET.

For flexure at 28 days, the combination that best fit was concrete with coconut fiber (AB), and for absorption, the combination that best fit was also concrete with coconut fiber (AB). All combinations are deemed ideal as their *p* values fell within the expected range (0.05) [44].

Table 8 presents the results for compression and flexure at 14 and 28 days, as well as absorption, which complements the information from Table 7. The R-squared (R^2) statistic indicates the variability percentage in the test results (compression, flexure, and absorption), while the adjusted R^2 value is used to compare models with a different number of independent variables.

The estimate's standard error shows the residuals' standard deviation, indicating dispersion among the data. Values closer to zero signify less data dispersion, while values farther from zero indicate greater dispersion. Based on this, it's understood that the data with the most dispersion are those for compression at 14 and 28 days, as their mean absolute

error (MAE) values are further from zero than in other cases, resulting in 3.047 for 14 days and 3.820 for 28 days.

The MAE is a key factor when comparing it with other test models, selecting the lowest value as the best fit. The Durbin-Watson statistic (DW) indicates whether there is autocorrelation in the data. A value of two signifies no autocorrelation, while values less than two indicate positive serial correlation (compression and flexure at 14 days), and values greater than two indicate negative serial correlation (compression and flexure at 28 days and absorption).

Table 8. Supplement for Quadratic Model Fitting Results.

Statistic	COMPRESSION (MPa)		FLEXURE (MPa)		ABSORPTION (%)
	14	28	14	28	
R^2 (%)	51.45	42.39	73.66	83.30	92.65
R^2 (adjusted by G.l.)%	34.11	21.82	64.26	77.33	90.03
Standard Error	3.04	3.82	1.20	0.28	0.31
MAE	1.87	2.69	0.77	0.20	0.18
Durbin-Watson Statistic	1.63	2.01	1.23	2.29	2.31
	$p = 0.2131$	$p = 0.5151$	$p = 0.0434$	$p = 0.7395$	$p = 0.7501$

3.2.3. Response Surface Methodology (RSM)

The graphs in Tables 9 and 10 depict a color bar where the lowest values are represented in dark blue, while the highest values are represented in shades of red for each analysis established in the response surfaces, considering the ANOVA results. These contour plots allow the visualization of the three-dimensional shape of a response surface, composed of contour lines that show the trends and curvatures corresponding to the component's values related to the analyzed variables, including flexure, compression, and absorption.

Response Surface Methodology (RSM) for Compression at 14 and 28 Days

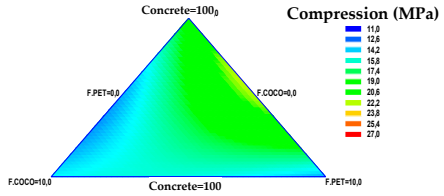
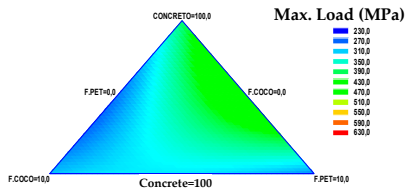
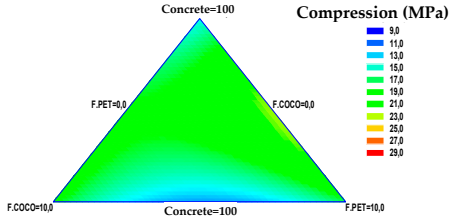
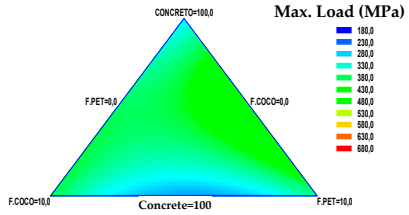
Based on Equations (7) and (8), the Statgraphics program generates graphs that allow us to study and interpret the behavior of mixtures regarding compression at 14- and 28- days. These graphs are known as Contour Plots and represent a 2D visualization using a continuous color range based on the ranges of the equation values [45].

$$\begin{aligned} \text{Compression 14} \quad &= (18.6383 \times \text{Concrete}) + (14.8475 \times \text{F.Coconut}) \\ &+ (13.5353 \times \text{F.PET}) - (13.1865 \times \text{Concrete} \times \text{F.Coconut}) \\ &+ (23.6045 \times \text{Concrete} \times \text{F.PET}) \end{aligned} \tag{7}$$

$$\begin{aligned} \text{Compression 28} \quad &= (14.1069 \times \text{Concrete}) + (18.3586 \times \text{F.Coconut}) \\ &+ (17.1047 \times \text{F.PET}) + (7.17715 \times \text{Concrete} \times \text{F.Coconut}) \\ &+ (27.9615 \times \text{Concrete} \times \text{F.PET}) \\ &- (23.0517 \times \text{F.Coconut} \times \text{F.PET}) \end{aligned} \tag{8}$$

Table 9 for compression at 14 and 28 days, exposing each with its respective maximum load, shows that at 14 days, the lowest results were found in combinations involving concrete and coconut fiber. An approach of 10% for coconut fiber was observed; the values take on a dark blue, indicating a reduced compression value. In the area where coconut fiber is absent and percentages of PET are present, the colors become darker (green), indicating higher compressions. In the zone where concrete accounts for 90% (base of the response surface contour) and with certain incorporations of PET and coconut, values are not as low as in the 100% coconut fiber zone and higher coconut percentages. Note that shades of dark and light blue are found on the contour side with combinations of both fibers. At 28 days, low compressions persist in combinations of both fibers, and it is noticeable that high compressions were achieved in combinations without coconut fiber.

Table 9. 2D RSM for Compression Tests at 14 and 28 days.

Days	Compression (MPa)	Max. Load (MPa)
14		
28		

RSM for Flexure at 14 and 28 Days

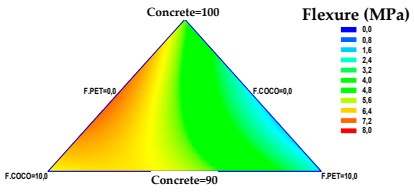
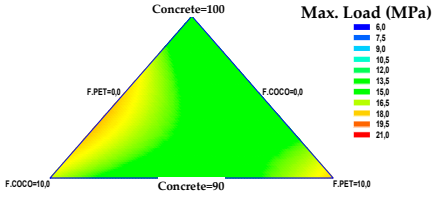
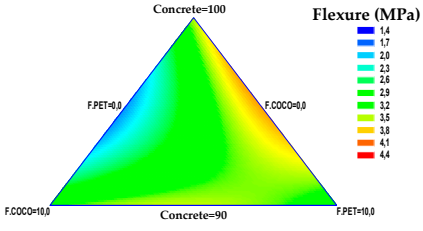
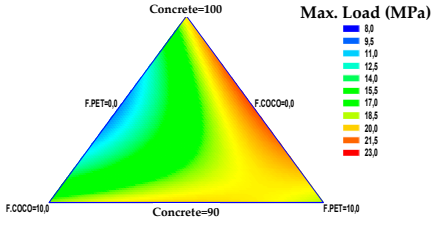
Based on Equations (9) and (10), the behavior at 14 and 28 days for flexure results can be analyzed in the contour plot [45].

$$\begin{aligned} \text{Flexure 14} \quad &= (5.29915 \times \text{Concrete}) + (5.90643 \times \text{F.Coconut}) + (2.24389 \times \text{F.PET}) \\ &+ (6.04721 \times \text{Concrete} \times \text{F.Coconut}) - (7.22296 \times \text{Concrete} \times \text{F.PET}) \\ &+ (6.34619 \times \text{F.Coconut} \times \text{F.PET}) \end{aligned} \tag{9}$$

$$\begin{aligned} \text{Flexure 28} \quad &= (3.47891 \times \text{Concrete}) + (3.26213 \times \text{F.Coconut}) + (3.06196 \times \text{F.PET}) \\ &- (6.25282 \times \text{Concrete} \times \text{F.Coconut}) + (2.52649 \times \text{Concrete} \times \text{F.PET}) \\ &+ (1.43938 \times \text{F.Coconut} \times \text{F.PET}) \end{aligned} \tag{10}$$

Table 10 shows that lighter colors (shades of blue) represent lower flexure values, while darker colors (red) represent higher flexure values. For flexure at 14 days, the highest values are reflected in the contour surface area where coconut fiber is present (right side of the contour plot) and in its central zone, affirming that the incorporation of coconut should not be at 10%, and its value decreases in the area where PET is present (right side of the contour plot). In the case of flexure at 28 days, the darker shades are in the area where certain percentages of coconut fiber and PET exist and with percentages where the coconut fiber approaches zero.

Table 10. 2D RSM for Flexure Tests at 14 and 28 days.

Days	Compression (MPa)	Max. Load (MPa)
14		
28		

RSM for Absorption

Equation (11) represents the behavior in terms of absorption that can be analyzed in the contour plot [45].

$$\begin{aligned} \text{Absorption} \quad &= (6.09946 \times \text{Concrete}) + (6.14539 \times \text{F.Coconut}) + (3.45369 \times \text{F.PET}) \\ &-(2.07149 \times \text{Concrete} \times \text{F.Coconut}) - (1.93826 \times \text{Concrete} \times \text{F.PET}) \\ &+(1.58545 \times \text{F.Coconut} \times \text{F.PET}) \end{aligned} \tag{11}$$

For concrete cobbles, the absorption rate should ideally be 7%, regardless of their dimensions [46]. In Figure 10, values ranging from 3.2 to 7.2 were observed, where higher values are represented by darker colors (shades of red), and lower values are represented by lighter colors (shades of blue). Therefore, it can be concluded that cobbles containing 10% coconut fiber achieve good absorption percentages comparable to cobbles made entirely of concrete. This conclusion is supported by the contour plot, where the darkest colors are found in the area where PET is almost absent and where there are percentages of coconut fiber.

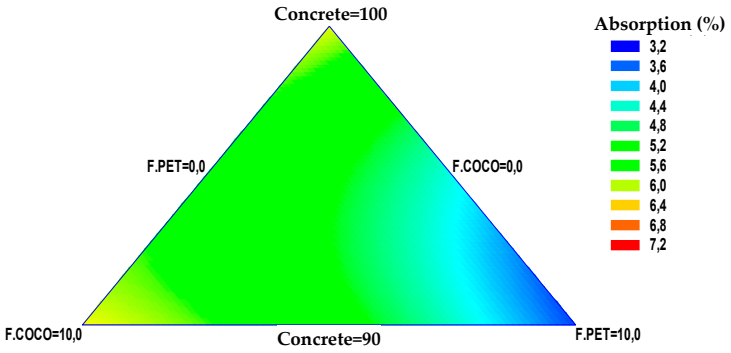


Figure 10. 2D plot for absorption results.

3.3. Response Optimization According to Statgraphics

Finally, the statistical analysis for each response variable concerning data optimization is presented. Proposing the percentage that maximizes the variables, as shown in Table 11, the optimal percentages to achieve better results in the variables for both 14 and 28 days are provided. Notably, in this case, flexure and compression are the variables for which optimization of values is sought.

For compression at both ages, the addition of coconut fiber should be almost negligible to maximize the compression value, corroborating the reduction in compression stresses with the addition of coconut fiber. This finding aligns with a study from Santa Elena Peninsula State University, which found a 26% reduction in compression stresses with the addition of coconut fiber at percentages of 10, 15, and 20% [26]. For flexure at 14 days, the addition of coconut fiber should be approximately 5% to maximize the flexure value, whereas, for 28 days, the value changes to almost nil. If flexure at 28 days is to be maximized, then the addition of coconut fiber provides improvements at an early age of 12. Regarding the addition of PET fiber, it is observed that as a material contributing to hardness and rigidity, it aids in reinforcing the concrete [10].

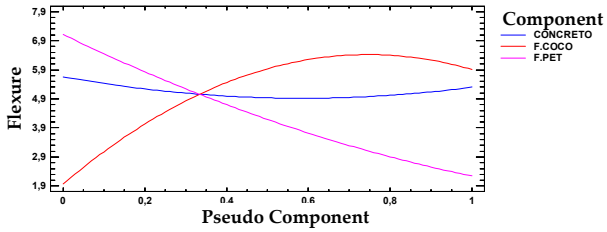
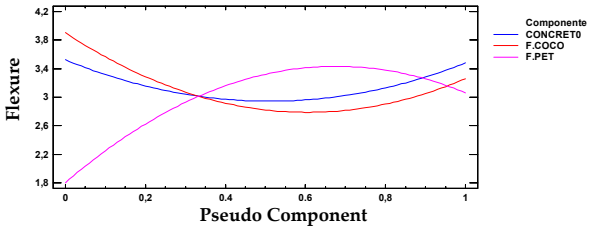
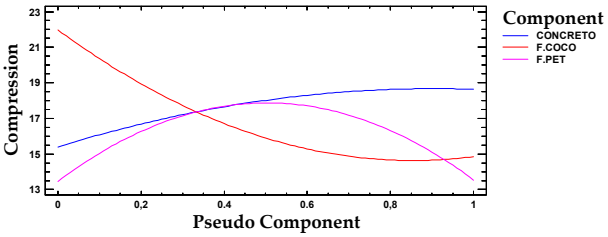
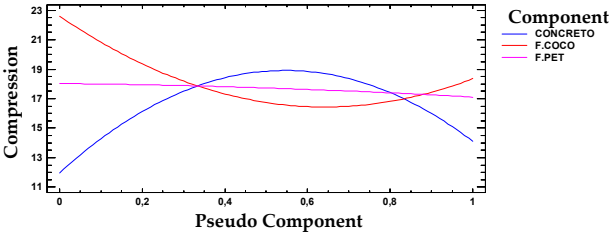
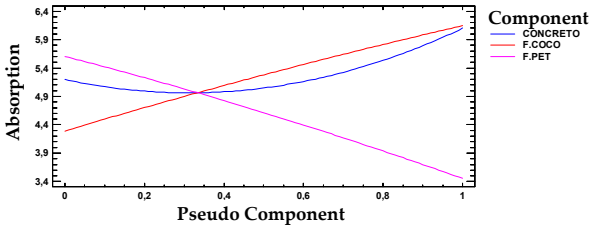
Table 11. Summary of optimal values to achieve maximized compression and flexure variables.

Test	Concrete (%)	F. Coconut (%)	F. PET (%)
Compression 14 days	96.08	1.8×10^{-8}	3.92
Compression 28 days	94.46	5.53×10^{-9}	5.55
Flexure 14 days	94.49	5.50	3.51×10^{-9}
Flexure 28 days	95.82	1.96×10^{-9}	4.17

Table 12 presents the dosage analysis where the three components correlate best, resulting in 93.3% Concrete, 3.33% coconut fiber, and 3.33% PET fiber (mixture 5). As can

be observed, the lines representing the three components converge at the same point, for which the *p*-value is consistently below 0.05.

Table 12. Trace graphs according to the components of concrete, coconut fiber, and PET fiber.

FLEXURE (MPa)	14	
	28	
COMPRESSION (MPa)	14	
	28	
ABSORPTION (%)		

Note: The blue line represents concrete, the red line represents coconut fiber, and the pink line represents PET fiber.

4. Conclusions

This research demonstrates that PET fiber significantly enhances compression strength in concrete mixtures. Mixtures with higher PET fiber content, such as the 95% concrete and 5% PET fiber mix (mixture 3), achieved compressive strengths of 26.8 MPa at 14 days and 28.7 MPa at 28 days, surpassing the target strength of 22 MPa. In contrast, coconut fiber had minimal impact on compression strength, highlighting PET fiber's superior role in improving concrete properties.

For flexural strength, adding coconut fiber reduced crack width compared to a 100% concrete paver (mixture 2), suggesting effective bridging of the concrete matrix by the fibers. Although flexural strength was higher at early ages, it decreased significantly by

28 days. For instance, mixture 8 (96.6% concrete, 1.6% coconut fiber, 1.6% PET fiber) showed the highest flexural strength of 6.6 MPa at 14 days but dropped to 3.2 MPa at 28 days.

Regarding water absorption, none of the mixtures exceeded the NTC 2017 limit of 8%. However, coconut fiber mixtures demonstrated higher absorption rates. The highest absorption occurred in the 10% coconut fiber mix (mixture 9), whereas PET fiber mixtures had lower absorption, particularly with 10% PET fiber (mixture 7). This increased absorption with coconut fiber may be linked to reduced flexural strength at 28 days due to ongoing curing.

The simplex-centroid design with a quadratic model effectively determined optimal dosages. PET fiber significantly improved compression strength, with effective dosages of 3.92% at 14 days and 5.53% at 28 days. For flexural strength, the optimal mixture included 5.5% coconut fiber at 14 days and 4.17% PET fiber at 28 days. These results should be validated with further testing.

Variance analysis supported the quadratic model's reliability, revealing that PET fiber is optimal for compression strength, while mixtures with both coconut and PET fibers excel in flexural strength. Positive correlations between compression and flexural strength were observed at 14 days, and negative correlations were observed between absorption and strength variables at 28 days.

Contour plots from the response surface graph highlight that high compression strengths are associated with minimal coconut fiber content. Flexural strength is higher at early ages without PET fiber and decreases with PET fiber presence by 28 days. Absorption is lower with 10% PET fiber, as shown by the dark blue in the PET fiber corner, with higher absorption values indicated by reddish tones.

Author Contributions: R.A.G.-L. contributed to the investigation, supervision, methodology, formal analysis, writing—original draft, writing—review, and editing. J.T.-C. and N.C.-Q. contributed to the investigation, formal analysis, and other contributions. N.A.-G. and J.G.-C. contributed to conceptualization, methodology, and other contributions. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by DIE UFPSO grant number 158–08–037.

Data Availability Statement: Data are contained within the article.

Acknowledgments: Thanks to the laboratory technicians of the Universidad Francisco de Paula Santander Oca-ña sede Invias for their support in the development of the tests.

Conflicts of Interest: The authors declare no conflicts of interest.

Symbology Lists

PET: Polyethylene Terephthalate
COMP: Compressive Strength
CAR.MAX: Maximum Load Capacity
TEN: Tension/Flexure
E = Modulus of elasticity (MPa)
ν = Poisson's ratio
fc' = Compressive strength (MPa)
ϵ = Unit strain
σ = Stress (MPa)
τ = Shear stress (MPa)
G = Shear modulus (MPa)
ρ = Density (kg/m^3)
ϕ = Diameter (mm)
d = Effective diameter (mm)
A = Area (mm^2)
L = Length (mm)
V = Volume (mm^3)
t = thickness (mm)
P = Load (N)

M = Bending moment (N mm)
Q = Shear force (N)
k = Thermal conductivity coefficient (W/m K)
Cp = Heat capacity (J/kg K)
α = Coefficient of thermal expansion (1/K)
T = Temperature (K)

References

1. Jaramillo, H.Y.; Vasco-Echeverri, O.H.; Moreno-Pacheco, L.A.; García-León, R.A. Biomaterials in Concrete for Engineering Applications: A Bibliometric Review. *Infrastructures* **2023**, *8*, 161. [CrossRef]
2. Rodgers, L. La enorme fuente de emisiones de CO_2 que está por todas partes y que quizás no conocías. *BBC Newa* **2018**, *17*, 12.
3. Greenpeace. La Contaminacion Plástica en Colombia y el Mundo. 2018. Available online: https://www.greenpeace.org/colombia/tag/plasticos/ (accessed on 13 June 2024).
4. Greenpeace. Situación Actual de Los Plásticos en Colombia y su Impacto en el Medio Ambiente. 2019. Available online: https://greenpeace.co/pdf/2019/gp_informe_plasticos_colombia_02.pdf (accessed on 13 June 2024).
5. DNP Colombia Rellenos Sanitarios de 321 Municipios Colapsarán en Cinco Años, Advierte el DPN. Available online: https://2022.dnp.gov.co/Paginas/Rellenos-sanitarios-de-321-municipios-colapsar%C3%A1n-en-cinco-a%C3%B1os,-advierte-el-DNP--.aspx#:~:text=Bogot%C3%A1%20(@DNP_Colombia).,disposici%C3%B3n%20final%20de%20residuos%20s%C3%B3lidos (accessed on 13 June 2024).
6. Jiménez, C.; Augusto, Q. Situacion del Coco en Colombia. 2012. Available online: https://sioc.minagricultura.gov.co/Coco/Normatividad/2012%20Acuerdo%20de%20Competitividad%20Coco.pdf (accessed on 13 June 2024).
7. Gestores de Residuos—Semana. Colombia: Encuentran Nuevos Usos a Los Desechos del Coco. 2021. Available online: https://www.semana.com/mejor-colombia/articulo/generar-ingresos-a-partir-de-la-basura-san-juan-de-uraba-encontro-la-formula-para-hacer-crecer-la-industria-del-coco-en-colombia/202100/ (accessed on 13 June 2024).
8. Vila, P.; Pereyra, M.N.; Gutiérrez, Á. Resistencia a la compresión de adoquines de hormigón. Resultados tendientes a validar el ensayo en medio adoquín. *Rev. ALCONPAT* **2017**, *7*, 247–261. [CrossRef]
9. Santillán, M.; Ciencia UNAM-DGDC. Concreto Reforzado con Fibras Aporta Beneficios a la Construcción. Available online: https://ciencia.unam.mx/leer/1069/concreto-reforzado-con-fibras-aporta-beneficios-a-la-construccion (accessed on 13 June 2024).
10. Saucedo Rodriguez, J.A.; Atoche Zamora, J.J.; Muñoz Pérez, S.P. Uso de los agregados PET en la elaboración del concreto: Revisión de la literatura. *Rev. Av. Investig. Ing.* **2021**, *18*, 1–12. [CrossRef]
11. Vidal, E.F. *Aplicacion de la Estopa de coco Para Mejorar la Resistencia de Adoquines de Concreto en la Calle San Juan-Manzana W1 Distrito de Independencia 2019*; Escuela Académico Profesional de Ingeniería Civil: Lima, Peru, 2019.
12. Mundaca, S.; Gonzales, F. *Incorporación de Fibra de Coco Para Mejorar la Permeabilidad del Adoquín en Vías Peatonales*; Universidad César Vallejo: Trujillo, Peru, 2019.
13. Yerramala, A.; Ramachandrudu, C. Properties of Concrete with Coconut Shells as AggregateReplacement. *Int. J. Eng. Invent.* **2012**, *1*, 21–31.
14. Mayancela, J.R. Analisis Comparativo de la Resistencia a Compresiòn Entre un Adoquìn Convencional y Adoquines Preparados con Diferentes Fibras: Sintètica(polipropileno), Orgànica(estopa de coco, Inorganica(vidrio). Bachelor's Thesis, Universidad Tecnica de Ambato, Ambato, Ecuador, 2021. Volume 593.
15. Quintero Garcia, S.L.; Gonzalez Salcedo, L.O. Uso de fibra de estopa de coco para mejorar las propiedades mecanicas del concreto. *Ing. Desarro.* **2006**, *20*, 135–150.
16. Yara-Amaya, F.A. Bioadoquines con Fibras de Coco y Fique, Nueva Apuesta en Construcción. Available online: https://agenciadenoticias.unal.edu.co/detalle/bioadoquines-con-fibras-de-coco-y-fique-nueva-apuesta-en-construccion (accessed on 13 June 2024).
17. Krishnamoorthy, M.; Tensing, D.; Sivaraja, M.; Krishnaraja, A.R. Durability Studies on Polyethylene Terephthalate (PET) Fibre Reinforced Concrete. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 634–640.
18. Saikia, N.; Brito, J. De Waste polyethylene terephthalate as an aggregate in concrete. *Mater. Res.* **2013**, *16*, 341–350. [CrossRef]
19. Di Marco Morales, R.O. Diseño y elaboración de un sistema de adoquines de bajo costo y material reciclado para construcciones en núcleos rurales. *Rev. ESAICA* **2015**, *1*, 30. [CrossRef]
20. Ascencio, E.; Montoya, L.; Campo, J. *Diseño y Elaboracion de un Prototipo de Pavimento Articulado "Adoplas" a Base de Plastico Residual Recuperado PET y PP*; Universidad Coperativa de Colombia: Bogota City, Colombia, 2021; Volume 15.
21. Omar, R.; León, H.A.; Ladrillos con Adicion de PET. Una Solución Amigable Para Núcleos Rurales del Municipio del Socorro. 2017. Available online: https://www.unilibre.edu.co/bogota/pdfs/2017/5sim/p/39D.pdf (accessed on 16 August 2024).
22. Peñaranda, M.; Rincon, M. *Analisis Comparativo del Comportamiento a Flexiòn y Compresiòn del Concreto con Adiciòn de Macro-Fibras de Plastico Reciclado*; Universidad Francisco de Paula Santander: Cúcuta, Colombia, 2014.
23. Florez, C. *Propiedades FFisico-Quimicas del Concreto de 24 MPa con el Uso de Polietileno de Tereflalato Reciclado(botella PET) y el Concreto Convencional en la Ciudad de Cucuta*; Universidad Francisco de Paula Santander: Cúcuta, Colombia, 2014.
24. Tami, J.; Landinez, P. *Analisis del Desempeño Mecanico y de Porosidad de una Matriz de Concreto Reforzado con Diferentes Porcentajes de Fibras de Tereftalato de Polietileno(PET) Reciclado*; Universidad Francisco de Paula Santander: Cúcuta, Colombia, 2017.

25. Manrique, A. *Influencia de la Adiciòn de Fibra de Coco en la Fromulacion de Pastas Ceramicas y su Efecto en el Comportamiento Fisico-Mecanico y Estructural*; Universidad Francisco de Paula Santander: Cúcuta, Colombia, 2017.
26. Lainez, W.L.; Villacis, S.A. *Hormigon Liviano con Desecho de coco Como Sustituto Parcial de agregado Grueso*; Universidad Estatal Peninsula de Santa Elena: La Libertad, Ecuador, 2015.
27. Ojeda, J.B. Uso del Cuesco de la Palma Africana en la Fabricación de Adoquines y Bloques de Mampostería. *Energy Technol. Am. Educ. Innov. Technol. Pract.* **2009**, 1–10. Available online: https://www.laccei.org/LACCEI2009-Venezuela/Papers/p202.pdf (accessed on 13 June 2024).
28. García-León, R.A.; Gómez-Camperos, J.A.; Jaramillo, H.Y. Scientometric Review of Trends on the Mechanical Properties of Additive Manufacturing and 3D Printing. *J. Mater. Eng. Perform.* **2021**, *30*, 4724–4734. [CrossRef]
29. Giraldelli, M.A.; Alves Pereira, O.; Dos Santos, S.F.; Aguiar Brasil, M.; Teodoro Pinheiro, S.K. Propriedade da Fibra de Coco: Uma Revisão Sistemática. *Uniciências* **2021**, *24*, 34–38. [CrossRef]
30. Chen, L.; Zhang, X.; Liu, G. Analysis of dynamic mechanical properties of sprayed fiber-reinforced concrete based on the energy conversion principle. *Constr. Build. Mater.* **2020**, *254*, 119167. [CrossRef]
31. Abdullah, S.; Abdulwahid, M. The Effect of Adding Different Types of Natural Fibers on Mechanical Properties and Impact Resistance of Concrete. *Res. J. Appl. Sci. Eng. Technol.* **2015**, *9*, 1091–1096. [CrossRef]
32. Alateah, A.H. Graphene concrete: Recent advances in production methods, performance properties, environmental impact and economic viability. *Case Stud. Constr. Mater.* **2023**, *19*, e02653. [CrossRef]
33. Hamada, H.M.; Shi, J.; Al Jawahery, M.S.; Majdi, A.; Yousif, S.T.; Kaplan, G. Application of natural fibres in cement concrete: A critical review. *Mater. Today Commun.* **2023**, *35*, 105833. [CrossRef]
34. INVIAS Sección 200. Man. Normas Ensayos Mater. Para Carretereas. 2013. Available online: https://www.umv.gov.co/sisgestion2019/Documentos/APOYO/GLAB/GLAB-DE-002_V1_Normas__Invia_Seccion__200-13.pdf (accessed on 29 November 2023).
35. García-León, R.A.; Flórez-Solano, E.; Rodríguez-Castilla, M. Application of the procedure of the iso 50001:2011 standard for energy planning in a company ceramic sector. *DYNA* **2019**, *86*, 113. [CrossRef]
36. *NTC-2017*; Adoquines de Concreto Para Pavimentos. Norma Técnica Colombiana: Bogotá, Colombia, 2018; pp. 1–20. Available online: https://tienda.icontec.org/gp-adoquines-de-concreto-para-pavimentos-ntc2017-2018.html (accessed on 29 November 2023).
37. *ACI-330R-08*; Guide for the Design and Construction of Concrete Parking Lots. ACI: Indianapolis, IN, USA, 2008. Available online: https://www.concrete.org/store.aspx (accessed on 7 December 2023).
38. Toirac Corral, J. Caracterización granulométrica de las plantas productoras de arena en la República Dominicana, su impacto en la calidad y costo del hormigón. *Cienc. Soc.* **2012**, *37*, 293–334. [CrossRef]
39. Rincon Cardenas, W.F.; Sanchez Torres, A.A.; Garcia Leon, R.A. *Análisis Bibliométrico y Experimental Sobre el Mejoramiento de las Propiedades Mecánicas del Cemento con el Uso de Aditivos*; Universidad Francisco de Paula Santander Ocaña: Ocaña, Colombiaia, 2022.
40. García-León, R.A.; Flórez Solano, E. Determinación de la ventana del proceso productivo en la fabricación de bloques H-10 en Ocaña Norte de Santander y la región. *Ingenio UFPSO* **2016**, *9*, 35–43. [CrossRef]
41. Bencardino, F.; Mazzuca, P.; do Carmo, R.; Costa, H.; Curto, R. Cement-Based Mortars with Waste Paper Sludge-Derived Cellulose Fibers for Building Applications. *Fibers* **2024**, *12*, 13. [CrossRef]
42. Minitab Explicación de las Sumas de Los Cuadrados. Available online: https://support.minitab.com/es-mx/minitab/help-and-how-to/statistical-modeling/anova/supporting-topics/anova-statistics/understanding-sums-of-squares/ (accessed on 13 June 2024).
43. García-León, R.A.; Martínez-Trinidad, J.; Guevara-Morales, A.; Campos-Silva, I.; Figueroa-López, U. Wear Maps and Statistical Approach of AISI 316L Alloy under Dry Sliding Conditions. *J. Mater. Eng. Perform.* **2021**, *30*, 6175–6190. [CrossRef]
44. García-León, R.A.; Martinez-Trinidad, J.; Zepeda-Bautista, R.; Campos-Silva, I.; Guevara-Morales, A.; Martínez-Londoño, J.; Barbosa-Saldaña, J. Dry sliding wear test on borided AISI 316L stainless steel under ball-on-flat configuration: A statistical analysis. *Tribol. Int.* **2021**, *157*, 106885. [CrossRef]
45. Statgraphics Resumen Captura de Datos Resumen del Análisis Gráfica de Superficie. Available online: https://www.statgraphics.net/wp-content/uploads/2015/03/Centurion-XVI-Manual-Principal.pdf (accessed on 13 June 2024).
46. Alfonso, O.M.L. Características y Cualidades de Los Adoquines de Concreto. 2023. Available online: https://360enconcreto.com/blog/detalle/adoquines-de-concreto/ (accessed on 1 December 2023).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.