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Use of Recycled Rubber Grain for the Elaboration of Ecological Paving Stones as Alternative to the Constructive Industry

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Abstract: This work was developed based on the hypothesis that recycled aggregates (recycled rubber grain) could be used as a substitute for fine aggregates (such as sand) in mortar used to manufacture construction elements, such as paving stones. Its content covers the results of the research on the physical-chemical properties of different dosages whose aggregate content was partially replaced by recycled rubber grain in different percentages. In addition, the evaluation of the mechanical properties of the dosages under study with conventional replicas through absorption, flexo-traction and compression tests is evidenced. The above allowed to determine that a different alternative for recycling can be provided since rubber grain can be used as a possible substitute for fine aggregate, due to the fact that ecological paving stones were obtained with 5, 7 and 9 percent instead of sand, which presented an absorption and flexural resistance above what is required by the Colombian technical standard.

Key words: recycled aggregates; experimentation; dosage; construction elements; Colombian technical standard

1. Introduction

Currently, the transportation sector is considered a tool for mass consumption because it transports personal items, food, and, typically, people.

According to studies by the Technical and Administrative Department of the Environment, in our country, this economic activity, in addition to creating a large number of jobs and supporting thousands of families, also has a serious impact on natural resources. This is the sector where the most petroleum products such as fuels and lubricants are consumed, where a large amount of waste such as tires, oils, and batteries are industrialized, and it generates 80 percent of air pollution in cities with large population centers, such as Bogotá.

For many years, while a percentage of tires have been reprocessed and used, another percentage has been placed in special disposal sites or dumped in the open and burned. This consequently creates visually incongruous environments and serves as a breeding ground for vectors such as mice, flies, and dengue fever, which are lethal when affecting the public health of the surrounding population [1].

It should be noted that the environmental problem lies not only in the exploitation of mining settlements, but also highlights the issue of waste generation such as tires, which increases proportionally with the vehicle fleet.

Thus, taking into account the above overview of the environment, the excessive generation of tires, and the scarcity of stone resources, the reuse of tires for the production of paving stones could be considered a measure to contribute to environmental benefits.

The project is designed to address the following factors: first, we will identify the environmental aspects and impacts caused by post-consumer tires. Second, we will explain the production of an environmentally friendly paving stone with the most appropriate dosages of recycled rubber grain, sand, and cement. Finally, we will evaluate its properties and characteristics through laboratory tests (water absorption, flexural strength, and compression strength) in accordance with the 2017 Colombian technical standard.

This research focuses on evaluating the viability of incorporating these tire residues as materials for the production of paving stones and assessing their technical feasibility. This recycled aggregate is characterized both physically and mechanically. This project, based on environmental sanitation guidelines, proposes the use of waste tires in the design of new construction materials and ultimately proposes their various uses, such as recreational parks, pedestrian walkways, and passive vehicular traffic areas.

2. Methodology

Regarding its scope, the following project refers to the types of explanatory research with a level of documentary and experimental research, since it seeks to compare, through the development of different technical procedures, the validity of the information acquired based on the data obtained, in addition, descriptive because an analysis will be carried out regarding the tabulated results in order to analyze the data and extract significant generalizations that contribute to knowledge. The research will have a quantitative approach, since it tries to quantify the problem and understand how widespread it is by searching for projectable results, which normally seek to measure the magnitude and go after statistical results that are interpreted objectively [2].

In the area of impact assessment, the methodology proposed by Conesa Fernández – Vítora (1995) was used, which proposes obtaining values from the qualitative and quantitative assessment of the identified environmental impacts, obtaining an interaction matrix for the impacts caused.

The ecological paving stone production process was carried out at the SOAL INGENIERIAS S.A.S laboratory facilities, taking into account the methodology they employ for paving stone manufacturing. The conventional method of pouring into molds or formwork is more feasible due to its low costs and the ability to achieve high production volumes.

One hundred ninety-two paving stones were produced, using five replicates per batch for each test to increase the degrees of freedom of the experiment and consequently reduce the experimental error in the design, making it sensitive to differences between treatments.

To evaluate the behavior of the recycled aggregate in the mixture, it was supplied at three different percentages: 5%, 7%, and 9%, compared to conventional fine aggregate.

Twelve replicas were made with the characteristics of a 0% commercial paving stone (control), and an additional twelve were made with 5%, 7%, and 9% rubber grain, respectively, by mixing dosage. The molds were made with twelve paving stones, allowing for two spares in case of defective stones or the need to repeat a test. This was done to increase the reliability of the experimental data. Five samples were subjected to an absorption test. Since this is not a destructive test, the samples could undergo a flexo-tensile test. Finally, five samples were subjected to a compression failure test.

To corroborate the experimental results, a completely randomized experimental design (RED) was used, since the source of disturbing variability is known and controllable (environmental conditions); there is no gradient that affects the test; it remains constant.

Once the results of the analysis of variance of the "RED" were obtained, the Dunnet test was used, which is the ideal test to use when one of the treatments is a control and thus compare the means between treatments.

3. Results and Discussion

3.1 Identification of environmental aspects and impacts because of the post-consumption of the tire

Taking into account the environmental factors that may be affected by improper tire disposal, the action and the environmental components affected were represented, resulting in the intersection with each cell based on the existing environmental impact.

Figure 1 presents the results of the environmental impact assessment resulting from improper tire disposal. Reference Source Not Found. environmental following the inappropriate disposal of the tires.

To determine the value of each box in the matrix, the subjectively proposed ratings were multiplied, preceded by signs depending on whether each impact is adverse or positive applying the equation of the importance of an environmental impact.

	BIOTICO					ABIOTICO									SOCIAL		
	Fauna			Flora		Aire			Suelo			Agua		Paisaje.	Demográfico		Cultural.
ACCIONES DEL PROYECTO.	Diversidad	Migraciones	Abundancia	C. Vegetal	Comunidades vegetales	Calidad	Nivel de olor	N. de ruido	C. de uso del suelo	Erosión	Calidad	Cantidad	Calidad	Contraste	Calidad de vida	Nivel de empleo	Cambios de estilo de vida
Disposición de las llantas				-23		-32					-41		-22	-44	-45		

Figure 1. Impact assessment (Source: Authors, 2018)

The impact matrix shows the interrelationship of the activity with each environmental component under consideration. For this activity, 17 cause-effect interactions occurred, of which only 6 interrelate, generating a negative impact.

Finally, once the importance of each impact was calculated and these values entered into the matrix, a qualitative analysis of the results was carried out, complementing the assessment process. The environmental impacts evaluated and identified were categorized according to their value. For this purpose, two categories were formed according to the table.

Table 1. Categorization of impacts

Ranges	I	Code
Compatible	(-10>l≥-25)	C
Compatible	(-10>1≥-25)	C
Moderate	(-25>l≥-50)	M
Moderate	(-25>I≥-50)	M
Moderate	(-25>I≥-50)	M
Moderate	(-25>I≥-50)	M

Source: Authors, 2018

Table 2. Mixture design for 1:2 dosage per m³ (a)

Material	Weight (kg)	Density (kg/m³)	Volumes (m³)	W. Ratio	V. Ratio
Cement	610	3,080	0.198	1.0	1.0
Water	366	1,000	0.366	0.6	1.8
Fine AGG.	1,100	2,500	0.44	1.8	2.0

Source: Authors, 2018

According to the table above, 33.33% are compatible impacts (16.66% corresponding to the biotic component and the other 16.66% to the abiotic component) and 66.66% are moderate impacts (16.66% to the social component and the other 49.9% to the abiotic component), yielding the following conclusions.

Improper disposal of tires could generate a compatible impact, affecting the biotic component associated with vegetation cover.

This activity could generate a moderate impact, affecting the abiotic component associated with air quality, as well as soil quality and landscape contrast (the latter having the highest value for this component), and finally, a compatible impact with the abiotic component, affecting water quality.

Improper disposal of tires could generate a moderate impact, affecting the social component associated with quality of life.

3.2 Preparation of an ecological paving stone with the most appropriate dosages of recycled aggregates, sand, cement, and water

Once the design was defined, the materials were homogenized. They were weighed according to the required quantities and mixed manually with shovels and trowels.

Figure 2. Mixing the materials and preparing the mix

The surfaces of the formwork that come into contact with the mixture must be greased using a mixture of burnt oil and water to facilitate subsequent removal of the paving stones. Once the materials were homogenized, they were poured into molds with a capacity for 12 paving stones, with dimensions of 100 mm wide by 200 mm long and 60 mm thick for each paving stone, as shown in Figure. 3. The lumps generated in all mixtures containing rubber were then manually removed to avoid cracked and cavities in the final product. After the crumbling was completed, the paving stones were vibro-compacted in the machine for a period of no more than five seconds.

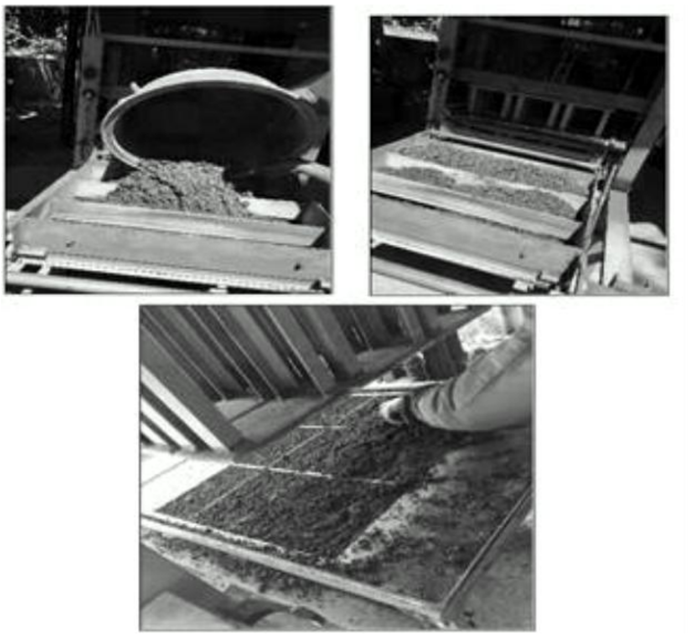


Figure 3. Casting and vibro-compaction process

After vibro-compaction was complete, the samples were moved to the setting process. All samples were prepared on the same day in the following order: first, the mixture for the conventional 1:2 ratio (control); second, the mixture with 5% recycled rubber granules; third, the mixture with 7% recycled rubber granules; and finally, the mixture with 9% recycled rubber granules. The paving stones were then prepared for the 1:3, 1:4, and 1:5 ratios in that order.

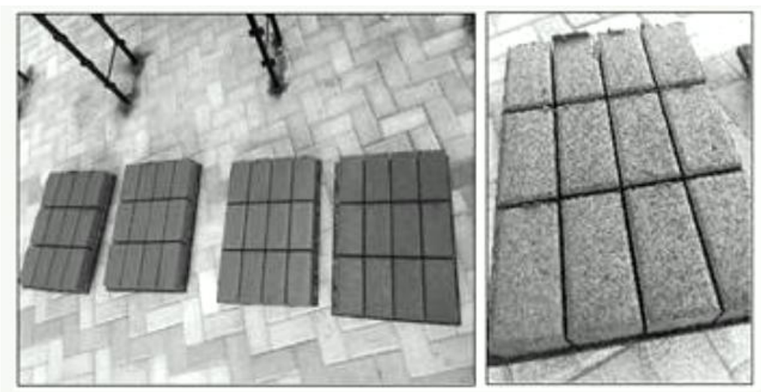


Figure 4. Setting and curing of the paving stone

3.3 Evaluation of the properties and characteristics of the paving stones through laboratory tests (water absorption, flexural-tensive, and compressive strength) in accordance with the 2017 NTC

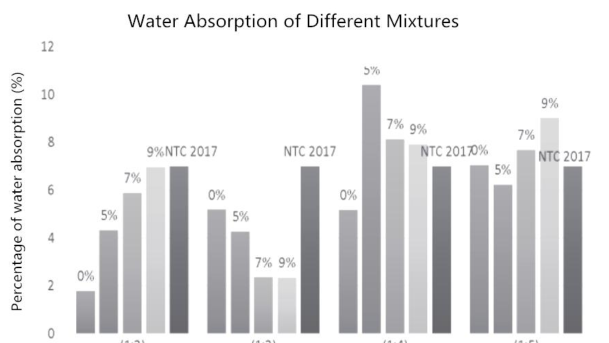
3.3.1 Water absorption

Five samples of each mixture were taken by dosage to perform the water absorption test. Each of the paving stones was designated with a number from 1 to 5 and the percentage of recycled material it contained. The dry weight of each specimen was subsequently measured. The test samples were then immersed in a container filled with water for 24 hours. After this time, they were surface-dried with a cloth. Immediately afterward, each saturated and surface-dry paving stone was weighed.

The test samples were then immersed for 24 hours in a container filled with water. After this time, they were dried superficially with a cloth and, without wasting time, each saturated and superficially dry paving stone was weighed.

Figure 5. 24-hour saturation and weighing of paving stones

Figure. 6 presents the behavior obtained between the different percentages of recycled aggregates replaced by natural aggregate with respect to the absorption by the paving stones, using the average value obtained for this as indicated by [6] "the concrete paving stones must have a total water absorption (Aa%) (for the entire volume of the specimen) not exceeding 7% as an average value for the specimens in the sample".



	(1:2)	(1:3)	(1:4)	(1:5)
0%	1,79	5,19	5,17	7,05
5%	4,33	4,28	10,41	6,23
7%	5,88	2,35	8,13	7,68
9%	6,96	2,34	7,93	9,02
NTC 2017	7	7	7	7

Figure 6. Comparison of water absorption for different mixtures

We proceed to interpret the results starting with the 1:2 ratio, which makes it clear that the greater the addition of recycled aggregates, the absorption in the specimens increases. However, the addition of the material does not generally affect the result, as all values meet the standard, being less than 7%.

The 1:3 ratio demonstrates that increasing the substitution of natural stone aggregates with recycled aggregates leads to lower average water absorption across five test specimens. This indicates stronger adhesion affinity between the recycled aggregates and the matrix at this ratio, while also conforming to the standards cited in [6]. Consequently, this ratio exhibited optimal performance in the absorption test.

It can be seen that the 1:4 ratio was the worst performer, as no ratio (with the exception of the control) met the standard. It is also worth noting that the higher the recycled aggregates addition, the lower the absorption of the paving stones.

Regarding the final dosage, it can be seen that even the dosage without added recycled aggregates (control) does not meet the maximum allowable absorption limit; only one dosage satisfies, and it is the one with the lowest percentage replaced. Furthermore, the greater the recycled aggregates replacement, the greater the absorption in the paving stones, which is not advantageous.

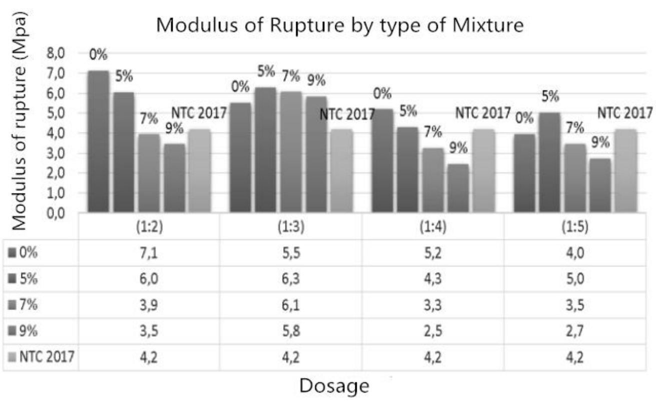
3.3.2 Flexural-tensile strength (modulus of rupture)

After the absorption test was completed, the five replicas were immediately used to undergo the flexural test (after marking the 10 mm gap on each side, as shown in Figure 7, as indicated by the standard, to take advantage of the surface-dry saturated process). The setup performed for this test is presented below:

Figure 7. Setup for 28-day flexural tensile test

The results presented are a summary of the calculation process after the preparation of each test at the facilities of the SOAL INGENIERIAS S.A.S. laboratory.

Figure 8. Pathological result of paving stone flexural failure



	(1:2)	(1:3)	(1:4)	(1:5)
0%	7,1	5,5	5,2	4,0
5%	6,0	6,3	4,3	5,0
7%	3,9	6,1	3,3	3,5
9%	3,5	5,8	2,5	2,7
NTC 2017	4,2	4,2	4,2	4,2

Figure 9. Comparison of the strengths of the modulus of rupture of the paving stones

The results obtained in the modulus of rupture test for the 1:2 ratio were expected to be closer to the standard requirements, as it contains more cement than the other ratios and only the control (which was expected to meet the standard), and the 5% replacement of RGC exceeded the value of 4.2 MPa. It is worth noting that the values for 7% and 9% are not that far from the target; they are very close to the requirements of the Colombian technical standard NTC.

The 1:3 ratio shows that the greater the replacement of stone aggregate with RGC, the lower the average modulus of rupture obtained across five specimens. However, they exceed the average value of the control. This not only exceeds the minimum value of the standard, but also means that the new RGC paving stone exceeds the strength limits of current traditional paving stones. From the above, it can also be concluded that the dispersion of (Mr) in the replacement of recycled material increases as a greater amount of RCC is replaced, showing yields of (14.54% for 5%), (10.9% for 7%), and (5.45% for 9%), above the 5.5 MPa average value of the samples.

An analysis of Figure 9 shows that in the 1:4 dosage, the greater the replacement of stone aggregate with RGC, the lower the average modulus of rupture obtained across five specimens. Only the average of the sample met the standard requirements. This indicates that making recycled paving stones with 5, 7, and 9 percent at 28 days of age does not achieve the strength required by the standard.

With a value of 5.0 MPa for the 1:5 mix and a 5% RGC content, it was the only higher value compared to the 4.2 MPa required by the Colombian technical standard NTC, even above the control value, which also performed poorly in this test. Basically, due to the inhomogeneous material in the mortar mix, the structural behavior of the paving stone produced highly dispersed results with sudden failures for the modulus of rupture.

3.3.3 Compressive strength

To perform this test, the five replicas were taken by dosage and percentage of RGC replaced, and then tested on the universal machine as shown in Figure 10. Each paving stone was designated with a number from 1 to 5 and the percentage of recycled material it contained. The paving stones were tested at 28 days of age, the same age as the previous tests.

Figure 10. Setup for 28-day compression test

The results shown below are a summary of the calculation process after the preparation of each test at the SOAL INGENIERIAS S.A.S. laboratory facilities.

Figure 11. Pathological result of compressive failure of the paving stone

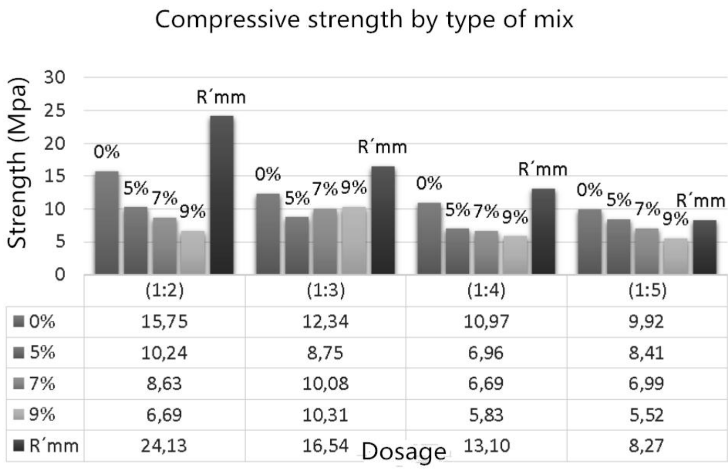


Figure 12. Comparison of compressive strengths of pavers

Evaluating the samples obtained 28 days after the different paving stones were cast, all dosages were unsatisfactory to the compressive strength for which the mortar was designed (R'mm), at the time of using the methodology by Rivera [4]. The greater the replacement of stone aggregate by GCR in general, a lower resistance was obtained by average of five specimens, however, it was evident that the mixtures with recycled aggregate content of 5%, 7% and 9% for the 1:3 dosage behaved in a similar way to the water absorption test (as the % to be replaced of GCR increases, the resistance increases), being indisputable that the paving stones for the 1:3 dosage had the best performance with the addition of GCR in all the tests to which they were subjected.

Table 3. Results of the experimental design (Dunnet's test)

Proof	Dosage	Dunnet test result			
Absorption	1:2	To-T1	-2.54	>2.02	SIG
		To-T2	-4.09	>2.02	SIG
		To-T3	-5.18	>2.02	SIG
	1:3	To-T1	2.10	>1.89	SIG
		To-T2	2.83	>1.89	SIG
		To-T3	2.84	>1.89	SIG
	1:4	To-T1	-5.24	>2.19	SIG

		To-T2	-2.96	>2.19	SIG
		To -T3	-2.75	>2.19	SIG
	1:5	To-T1	0.82	<3.00	N.SIG
		To-T2	-0.64	<3.00	N.SIG
		To-T3	-1.97	<3.00	N.SIG
Flexotraction	1:2	To-T1	1.08	<1.18	N.SIG
		To-T2	3.18	>1.18	SIG
		To-T3	3.66	>1.18	SIG
	1:3	To-T1	-0.76	<1.46	N.SIG
		To-T2	-0.50	<1.46	N.SIG
		To-T3	-0.30	<1.46	N.SIG
	1:4	To-T1	0.88	<1.17	N.SIG
		To-T2	1.90	>1.17	SIG
		To-T3	2.72	>1.17	SIG
	1:5	To-T1	-1.04	>0.90	SIG
		To-T2	0.50	<0.90	N.SIG
		To-T3	1.24	>0.90	SIG
Compression	1:2	To-T1	5.51	>1.33	SIG
		To-T2	7.13	>1.33	SIG
		To-T3	9.06	>1.33	SIG
	1:3	To-T1	3.79	>1.74	SIG
		To-T2	2.46	>1.74	SIG
		To-T3	2.23	>1.74	SIG
	1:4	To-T1	4.01	>1.95	SIG
		To-T2	4.28	>1.95	SIG
		To-T3	5.13	>1.95	SIG
	1:5	To-T1	1.51	<1.89	N.SIG
		To-T2	2.93	>1.89	SIG
		To-T3	4.40	>1.89	SIG
Note: SIG = Significant; N.SIG = NO Significant					

Thus, the results obtained in the experimental design and the application of the Dunnet test were related to those obtained experimentally, and in that order of ideas, the data obtained experimentally were statistically justified.

4. Conclusion

Four mix dosages were designed, and pedestrian paving stones were manufactured with 5, 7, and 9 percent recycled rubber grain in proportion to the sand in each design. Pavers without recycled rubber grain were manufactured (controls) for comparison purposes. According to the national standard NTC 2017, water absorption for paving stones should not exceed 7% as an average of five specimens. The results obtained after 28 days showed that only the 1:2 and 1:3 dosages satisfactorily meet the standard's requirements, while the 1:4 and 1:5 dosages do not meet the minimum value indicated by the standard (with the exception of 1:5 with 5% replacement). In this case, the absorption percentage tends to be high and, consequently, unfavorable. This can be attributed to the fact that the calculated dosages for 1:4 and 1:5 required a larger amount of fine aggregate for the mix, so the percentages to be replaced by (5, 7, 9%) increased in volume. The best-performing design mix, according to the results obtained, was the 1:3 mix with 9% RGC, followed by its replacement at 7% RGC, and then at 5% RGC.

The highest Modulus of Rupture (MR) achieved in the tests on the recycled paving stones, in compliance with the Colombian technical standard NTC, were again obtained with the 1:3 dosage, this time with 5% GCR, followed by its replacement with 7% GCR, and then with a 9% GCR replacement percentage. These values were even higher than those of the control sample, proving that, for the 1:3 dosage, GCR provides special characteristics that contribute to an increased Modulus of Rupture. Furthermore, it was proven that replacing 5% GCR in the 1:2, 1:4, and 1:5 dosages meets the standard's required value of 4.2 MPa.

It was found that when the paving stones were subjected to compression testing for their initially designed strength, they did not achieve satisfactory results; therefore, this additional indicator in the research was unsuccessful.

In this order, the research established that a 1:3 ratio obtained the most optimal proportions with recycled aggregates (RCG) for the manufacture of paving stones that comply with the Colombian technical standard NTC 2017. The project's main motivation, which was to provide an alternative for recycling rubber (a material that is not biodegradable by the environment), was met. The hypothesis was confirmed that the use of recycled aggregates (RCG) is easily applicable in small paving stone production industries, "replacing small quantities", indicating savings in fine aggregate. This savings in raw material (sand), from an environmental perspective, mitigates potential impacts resulting from activities such as "natural quarrying" and avoids creating scenarios that are sources of pollution and environmental degradation.

5. Recommendations

- Use the final mortar ratio of 1:3 (one cement to three sand) to study higher substitution percentages, as this yielded the most optimal results. The ratio was limited to 5, 7, and 9 percent, maintaining the methodology proposed by (Rivera, 2013).
- Regarding the paving stone production process, continue with the vibro-compaction process, as these mixers are excellent for this type of mixture and provide homogeneity and cohesion in the paving stones, thus improving their final strength.
- It is essential that when mixing the materials, they must first be dry mixed to ensure the homogeneity of the mixture during hydration.

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Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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