

Article

Mechanical Properties of Concrete Using Recycled Aggregates Obtained from Old Paving Stones

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Abstract: Nowadays, construction, maintenance, reparation, rehabilitation, retrofitting, and demolition from infrastructure and buildings generate large amounts of urban waste, which usually are inadequately disposed due to high costs and technical limitations. On the other hand, the increasing demand for natural aggregates for concrete production seriously affects mountains and rivers as they are the source of these nonrenewable goods. Consequently, the recycling of aggregates for concrete is gaining attention worldwide as an alternative to reduce the environmental impacts caused by the extraction of nonrenewable goods and disposal of construction and demolition waste (C&DW). Therefore, this article describes the effect on the mechanical properties of new concrete using recycled aggregates obtained from old paving stones. Results show that replacing 50% by weight of the fine and coarse aggregate fractions in concrete with recycled aggregate does not meaningfully affect its mechanical behavior, making the use of recycled aggregates in new precast paving stones possible. Therefore, the latter can reduce environmental impacts and costs for developing infrastructure and building projects.

Keywords: paving stones; aggregates; C&DW; sustainability; mechanical properties; concrete



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1. Introduction

The consumer society, together with the technological revolution, has led to the most massive production of waste in humanity's entire history. This problem has led to most countries seeking solutions to decrease pollution rates on the planet [1]. According to John [2], the construction industry produces 40% of the different world economic sectors' waste. On the other hand, with the pivotal role that the construction industry has in developing countries, it is convenient to adopt urgent measures to achieve sustainable development [3].

The construction industry is still one of the largest waste generators today [4–6]. However, historically it has been a necessary pillar for the development of our communities. In general, the construction sector's pollution occurs in most stages: from the extraction of raw materials, the manufacture of materials, to the different activities carried out during the construction, operation, and end of the life cycle of buildings and infrastructure. This causes the depletion of various nonrenewable resources, as well as water and air pollution, in addition to excessive energy consumption [7].

1.1. Global Context

In other industrial sectors, recycled materials are typically competitive when there is difficulty in obtaining virgin raw materials and suitable locations for storage. Therefore, the proposal for sustainable concrete is based on the substitution of stone aggregates

of natural origin for construction and demolition waste (C&DW), and it proves to be very interesting for infrastructure and buildings, enabling the implementation of circular economic models [8–10]. The government requirement to mitigate the environmental impact of the different construction projects through the proper management of the C&DW potentiates their reincorporation into the construction production chain through recycling. However, to use this waste in new projects, it is necessary to evaluate the physical, chemical, mechanical, and durability characteristics of the C&DW [11–13]. The use of C&DW as aggregates of concrete mixtures without knowing their properties can generate projects with concrete properties in a fresh and hardened state that are undesirable and unsafe for its users.

In the construction sector, a large amount of waste of different types is generated, but only a part of it can be reincorporated in the same sector, either by reusing or recycling it. C&DW must be inert and uncontaminated. Although there are significant fluctuations in Colombia, it can be estimated that the usable waste is 80% of the CDW, which is made up of materials such as bricks or blocks, concrete, rock, excavation material, steel, wood, and others [14]. The remaining 20% that is not usable in the construction sector (wood, plastics, packaging, and inert materials with organic matter) should be sent to specific recycling plants for industrial symbiosis or disposed in landfills [15].

To recycle concrete waste into new building products, intensive research worldwide, demonstrating that in general, the use of recycled aggregates from concrete in new fabrication of concrete has resulted in enhanced improvement of mechanical properties [16–19]. Perez-Benedicto et al. [20] studied the mechanical behavior of concrete made with recycled aggregate coming from discarded concrete prefabricated units, demonstrating that including coarse aggregate replacement can offer excellent quality for structural applications providing similar compressive strength respect conventional concrete. Cakir and Dilbas [21] demonstrated that durability of concrete can be increased up to 60% using recycled aggregate and an optimized ball mill method. The study included comparison of several aggregates such as natural aggregate, recycled aggregate, silica fume, basalt fiber and recycled aggregate and optimized ball mill method.

Vedrtnam et al. [22]. studied the response of cement-based composites under direct flame conditions, demonstrating improvement in the residual compressive strength compared to conventional concrete after the thermal exposure. In addition, it was found minimum damage in the microstructure of the material when residues of PET bottles are included in the mixture. Zareei et al. [23]. analyzed the combination of recycled waste ceramic aggregates and waste carpet fibers to produce high strength concrete. They used combinations from 20% up to 60% of recycled waste ceramic to replace natural coarse aggregate. As result it was observed an increase of compressive, splitting tensile, flexural and tensile strengths by 13%, 15%, 3% and 21% respectively. Zahid-Hossain et al. [24]. also studied the inclusion of recycled material as rubber and polypropylene fibers into concrete mixtures to evaluate their mechanical behavior. As result it was demonstrated that compressive strength, splitting tensile strength and flexural strength decreases as the crumb rubber content increases, and increase with the fiber content. In addition, it was observed a reduction in the propagation speed of failures in the material, providing a more gradual failure propagation.

On the other hand, several studies have demonstrated decrease in mechanical properties when replacing virgin aggregate with recycled aggregate. Alam et al. [25] found that replacements of 25% using recycled aggregate can reduce compressive strength of concrete in 15%. Similarly, Meherier [26] studied the replacement of aggregates using crumb rubber and obtained reductions of 20% in concrete compressive strength. Limbachiya et al. [27] found that replacements with recycled concrete higher than 30% affect drastically compressive strength. However, all previous studies did not follow a standard procedure and therefore results can vary from region to region and according to environmental and methodological tasks.

1.2. Colombian Context

In Colombia, large amounts of construction and demolition waste (C&DW) produced by the construction industry are inadequately disposed (Figure 1a,b). Similarly, large amounts of nonrenewable resources are converted illegally, by industrial processing, into construction materials (Figure 2a,b).



Figure 1. Inadequate disposal of construction and demolition waste (C&DW) in Colombia. (a) “Estación de Transferencia (EDT) de la Carrera 50” located in Cali [28]; (b) Cauca River [29].

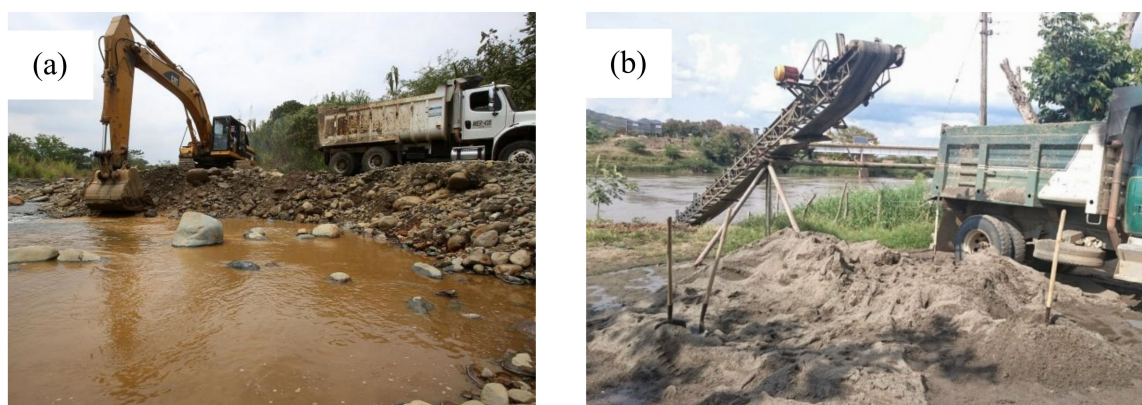


Figure 2. Illegal extraction of raw materials for construction in Colombia. (a) Rock extraction from Pance River [30]; (b) sand extraction from Cauca River [31].

Based on those above-mentioned environmental and social problems, a circular economy strategy from the national government has been launched. Particularly for C&DW, more than 22 million tons generated yearly in major cities should be waste managed [32]. On the other hand, the most widely used materials in the construction industry have historically been: aggregates, wood, concrete, steel, and glass. Except for aggregates and wood, the rest are composite materials that are made from nonrenewable raw materials. They are also the predominant materials in the last hundred years in large, intermediate cities and, unfortunately, even in the most remote rural areas [33].

So far, the construction of infrastructure and buildings has become one of the country’s main economic activities. Despite the social benefits that the previous process has brought, cities and rural environments face significant environmental challenges due to the demand for nonrenewable resources generated by urban centers. For example, the problem of consuming nonrenewable natural resources for concrete production in Colombia is growing, with increases in concrete production of around 6% per year [34]. This generates critical environmental problems derived from the manufacture of concrete, such as the requirement of large quantities of stone material used in the natural stage as fine and coarse aggregates,

and for producing Portland cement [35]. Commonly sand from the riverbed is used as a fine aggregate, while extraction and crushing of rock from quarries, usually rocky mountains, is carried out for the coarse aggregate. This situation poses significant technological challenges such as reduction, reuse, and recycling applied to all the country's productive sectors for the genuinely sustainable development of Colombian cities and municipalities.

In the case of Colombia for example, Diosa [36] performed an experimental analysis of mechanical properties of high-strength concrete from recycled sources, obtaining significant improvements in terms of mechanical resistance and durability. Hurtado [37] studied the effect of partial replacement of Portland cement by ash from the paper industry in the manufacture of mortar samples; results demonstrated that it is possible to obtain better mortar workability but less mechanical resistance. Moreover, Londoño [38] developed an analysis to determine the technical and financial suitability of using in situ recycled aggregates to fabricate prefabricated elements for construction.

In summary, the high demand for concrete, the natural resources for its production, and the generation of construction and demolition waste motivate the development of studies in which some waste is used and incorporated into the production of materials such as concrete [39,40]. Therefore, in this article, the mechanical performance of new concrete paving stones made with recycled aggregates from old paving stones in the municipality of Almaguer (Cauca, Colombia) were evaluated to be used for the same application in the municipality. The novelty of this research is focused in the use of aggregate to recirculate material within the same application and location, without incur in additional costs and using conventional crushing and laboratory equipment. The proposed method provides useful insights to recycle C&DW in the Colombian context and similar countries to fabricate added value products and lower environmental impact. The subsequent sections of this paper are organized as follows: Section 2 summarizes the materials and methods employed to conduct the experimentation and analyze the mechanical performance of concrete mixtures. Results are presented in Section 3, while Sections 4 and 5 correspond to discussion and conclusions.

2. Materials and Methods

This section summarizes the materials used to manufacture the paving stones and the methodology to analyze and compare mechanical properties. Materials mainly consist of used pavers, cement, coarse and fine aggregates (from natural sources and recycled). The proposed methodology started performing an aggregate sampling to classify materials, followed by a characterization of components, mixture design, evaluation of mechanical properties, and selecting the most suitable mixture concentrations to manufacture new paving stones.




2.1. Materials

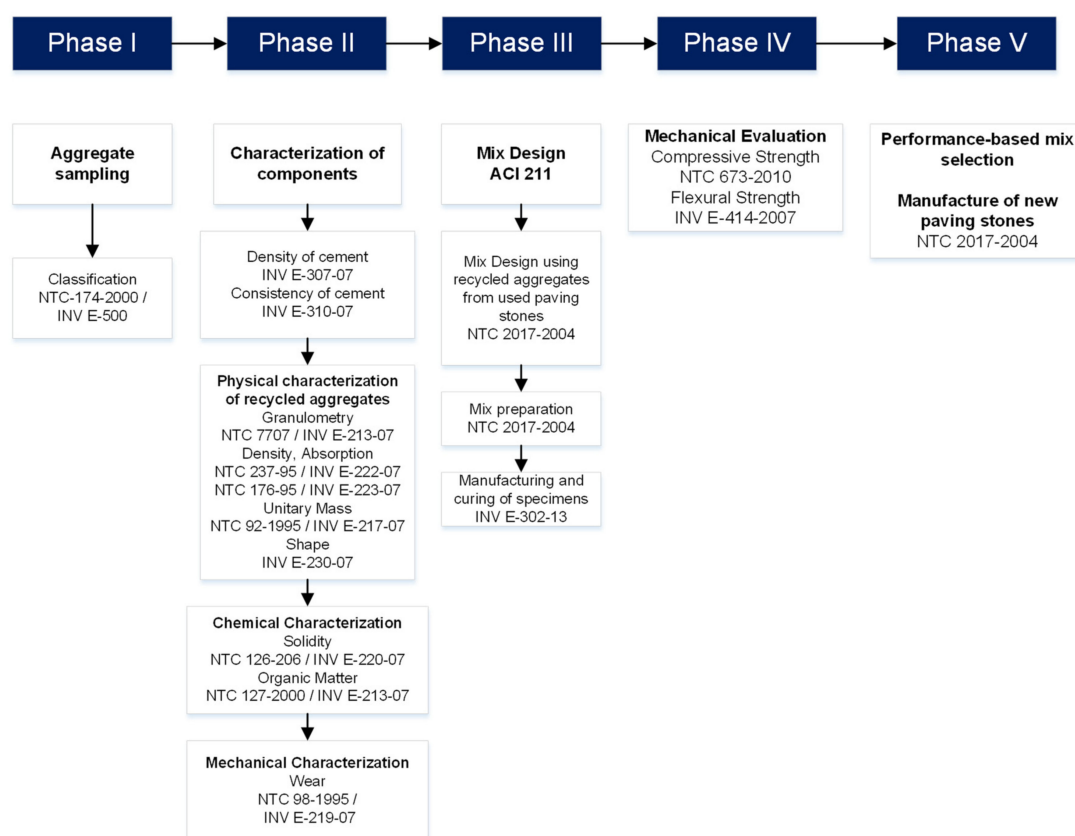
Table 1 shows the materials employed to manufacture and analyze concrete samples. It included used paving stones converted into recycled aggregates, natural aggregates, and Portland cement. Such materials are processed and converted into new concrete samples, which are later analyzed and tested to measure and compare conventional values of mechanical properties (flexural and compressive strength).

2.2. Method

The proposed methodology for this study consisted of five phases, which are oriented to generate and establish suitable concrete mixtures. Figure 3 shows the overall methodology followed in this article.

Table 1. Description of components involved in the manufacturing of paving stones.

Component	Sample Picture	Description
Used Pavers: Initial form—before grinding and transformation into recycled aggregate		Used pavers present cracks, voids, flaking, damage of edges, and require replacement. The study employed 200 used pavers for analyzing and generate new ones (converting used pavers into recycled aggregates) and compare pavers manufactured using natural aggregates.
Aggregates: From natural source (quarry) and used paving stones (recycled)		Detailed characterization can be found in further sections.
Portland Cement: Obtained from a local supplier		Ordinary Portland cement (OPC) Density of 3.1 g/cm ³ Consistency of 26.4% (Portland type I) Detailed characterization can be found in further sections.

**Figure 3.** Methodology followed during this research project.

As a first stage, the process started with collecting used paving stones, which corresponded later to recycled aggregates (coarse and fine). Such components were triturated until obtaining the desired granulometry according to the NTC 174 standard [41]. In a parallel process, natural aggregates were also obtained from a quarry to compare and create different concrete mixtures, varying the percentage of recycled material. The second stage was denominated characterization of components, and it aimed to determine the most relevant properties of all materials used during the experimentation process; such materials comprise cement and aggregates. Here, physical characterization was performed analyzing granulometry, specific weight and absorption, the unitary mass of CDW and natural materials, shape, elongation, compressive indexes, and density and consistency of Portland cement. Besides, a chemical characterization that included sulfide resistance and organic material analysis. Later, mechanical characterization covered the response under wear conditions. The third state covers the mixture design, the manufacturing of concrete specimens for mechanical tests after curing processes. Evaluation of mechanical properties was performed as the fourth stage, and it included experimental tests for compression and flexural strength of concrete specimens. Lastly, step five concludes the proposed methodology by manufacturing the paving stones using the most suitable mixture obtained from tests and analysis of previous phases. Table 2 summarizes the overall composition of the nine concrete samples selected for analyzing and performing mechanical tests.

Table 2. Composition of concrete samples for evaluating mechanical properties of concrete.

Mixture	Type of Aggregate		Number of Samples (28 Days of Age)	
	Coarse	Fine	Flexural	Compressive
M1	100% NAT + 0% RC	100% NAT + 0% RF	3	3
M2	100% NAT + 0% RC	50% NAT + 50% RF	3	3
M3	100% NAT + 0% RC	0% NAT + 100% RF	3	3
M4	50% RC + 50% NAT	100% NAT + 0% RF	3	3
M5	50% RC + 50% NAT	50% RF + 50% NAT	3	3
M6	50% RC + 50% NAT	0% NAT + 100% RF	3	3
M7	0% NAT + 100% RC	100% NAT + 0% RF	3	3
M8	0% NAT + 100% RC	50% RF + 50% NAT	3	3
M9	0% NAT + 100% RC	0% NAT + 100% RF	3	3
Total samples			27	27

M: mix, NAT: natural aggregate, RC: coarse recycled aggregate, RF: fine recycled aggregate.

To develop the five phases previously shown in Figure 3 it was necessary to perform several task and analysis activities to obtain a proper mixture of concrete including recycled aggregates. Such phases were performed using as reference the Colombian normative (NTC standards), and national road standards (INVIAS) which are adaptations of American Society for Testing and Materials (ASTM) standards (Appendix A). A brief description of each phase is presented as follows:

Phase 1 consisted of obtaining the samples of recycled and natural aggregates and classifying them according to the standard NTC-174 /INV E-500. Later, phase II included physical, chemical and mechanical characterization of aggregates and cement. Density and consistency of cement were determined using the INV-E-307/310 standards; physical characterization of aggregates comprised granulometry (NTC 7707, INV-E 213), density (NTC 237, INV E-222), water absorption (NTC 176, INV E-223), unitary mass and shape (NTC 92, INV E-217 and INV E-230); chemical characterization covered solid analysis (NTC 126, INV E-220) and organic matter (NTC 127, INV E-213); and, wear behavior (NTC 98, INV E-219) as mechanical characterization.

Phase 3 included mixture design, which is performed using the American Concrete Institute ACI 211 method (also equivalent to NTC 2017 standard). This method consists of selecting amounts of cement, aggregates, water and additives to produce cost-effective concretes able to obtain a desired mechanical strength, durability, stability, unitary mass, and appearance. In this case nine mixtures were proposed varying the percentage of natural and recycled aggregates. Phase 3 also comprised the curing process of concrete specimens

following the standard INV E-402. Then, when specimens were fabricated, it is necessary to perform mechanical tests to validate and compare flexural and compressive strength (NTC 673 / INV E-414) respect to conventional concrete mixtures in Phase 4. Lastly, Phase 5 consisted of selecting the best performance mixtures in terms of mechanical properties to fabricate new paving stones. Such fabrication was developed using the standard NTC 2017.

3. Results

This section comprises the results of five phases previously mentioned in the methodology. Section 4 is later presented to elucidate findings and interesting topics identified from the obtained results.

3.1. Aggregate Sampling

Natural aggregate samples were obtained from the company Canteras de Ingeocc S.A. (Yumbo, Colombia). On the other hand, used paving stones for recycled aggregates were obtained from the Almaguer's municipality (Cauca, Colombia). One hundred used paving stones were processed three times using a jaw crusher until acceptable sizes were obtained for an aggregate. The natural and recycled aggregates were classified into coarse and fine according to standard NTC 174 related to prefabricated paving stones. Approximately 530 kg of both natural and recycled aggregates were used during this study.

3.2. Characterization of Components

Physical and chemical attributes of interest were analyzed to determine the suitability of components to manufacture new concrete mixes. This subsection includes physical, chemical, and mechanical characterization. Physical characterization included several measurements and tests in determining key parameters in aggregates and cement employed: granulometric analysis, specific weight, water absorption, unitary mass, flattening, and elongation indexes for aggregates. In the case of cement, we determined density and consistency. Secondly, chemical characterization was dedicated to analyzing the chemical response of aggregates to sulfides (solidness) and analyzing the organic matter. Lastly, mechanical characterization was the first stage and consisted of a wear analysis for natural and recycled aggregates. Each characterization result is described in detail, as follows in Table 3. Additional properties of materials are summarized in Appendix B.

Table 3. Physical, chemical, and mechanical characterization of aggregates and cement.

Type of Characterization	Parameter	Component	Results
Physical	Granulometric analysis	Aggregate	Natural: Maximum size of 12.50 mm (coarse) and 9.50 mm (fine). Fineness module of 2.96 mm (coarse) and 2.97 mm (fine).
			Recycled: Maximum size of 12.50 mm (coarse) and 4.76 mm (fine). Fineness module of 5.44 mm (coarse) and 3.06 mm (fine).
	Specific weight	Aggregate	Natural: 2.8 g/cm ³ for fine and 2.93 g/cm ³ for coarse Recycled: 1.98 g/cm ³ for fine and 1.89 g/cm ³ for coarse
	% absorption	Aggregate	Natural: 1.6 for fine and 1.4 for coarse Recycled: 14 for fine and 15 for coarse
	Unitary mass	Aggregate	Natural: 1460 g/cm ³ for fine (l) and 1530 g/cm ³ for fine (c) 1600 g/cm ³ for coarse (l) and 1710 g/cm ³ for coarse (c)
			Recycled: 1250 g/cm ³ for fine (l) and 1422 g/cm ³ for fine (c) 1123 g/cm ³ for coarse (l) and 1232 g/cm ³ for coarse (c)
	Flattening and elongation Indexes	Aggregate	Natural: % flattening index: 26 and % elongation index: 20 Recycled: % flattening index: 9.51 and % elongation index: 3.27
	Density	Cement	3.1 ± 0.1 g/cm ³
	Consistency	Cement	26.4%

Table 3. Cont.

Type of Characterization	Parameter	Component	Results
Chemical	Solidness: resistance to sulfide	Aggregate	Natural % material loss: 1.4 (fine) and 3 (coarse) Recycled: % material loss: 86 (fine) and 66 (coarse)
	Organic Matter	Aggregate	Natural: 2 (number of organic reference) Recycled: 1 (number of organic reference) Both values below 3, which is the limit value for use in concrete
Mechanical	Wear	Aggregate	Natural % wear: 23 Recycled % wear: 64

l: loose; c: compact.

3.3. Mixture Design

This phase consisted of nine steps, which are summarized as follows in Table 4. According to Sánchez de Guzmán [42], calculations and analysis during this phase were performed meeting the requirements of the standard NTC 2017 [43], which implies a compressive strength of 50 MPa and flextraction of 5 MPa. The mixture design did not consider severe conditions (e.g., freeze-thaw cycles).

Table 4. Steps and their outputs during the mixture design phase.

Task	Results and Outputs
(i) Settling selection	An average value of 10 mm was selected. A very dry consistency is recommended for paving stones and implies the use of extreme vibration and possible pressure for achieving the desired compaction (recommended settlement: 0–20 mm).
(ii) Selection of maximum aggregate size	According to granulometry analysis, the maximum and maximum nominal size of aggregates corresponded to 12.5 mm (1/2") and 9.51 mm (3/8"), respectively.
(iii) Air content estimation	Since paving stones are not exposed to extreme conditions (freeze-thaw cycles), the concrete's air content is zero.
(iv) Estimation of mixing water content	This was performed using a linear regression between values provided, and using a value of settlement of 10 mm, which establishes that for settlement of 0 mm and 25 mm are required 201 kg and 208 kg of mixing water content respectively per 1 m ³ of concrete. The resulting value of mixing water content was 203.8 kg per 1 m ³ .
(v) Determination of design resistance	According to standard NTC 2017, a paving stone unit must provide a minimum modulus of rupture of 4.2 MPa after 28 days. Such modulus of rupture commonly varies between 10% and 20% of the compressive resistance. Therefore, as an indirect measurement, minimum compressive resistance of the mixture of 42 MPa is required. To compensate for possible fluctuations, it is desirable to include a safety factor. Following the standard NTC 2017, 100 kg/cm ² were added to the compressive resistance, thus an approximate compressive resistance of 50 MPa (520 kg/cm ²).
(vi) Selection of water/cement ratio	This was established according to the water/cement ratio values provided by. This establishes that for a value of 520 kg/cm ² the corresponding water/cement ratio is equal to 0.36.
(vii) Calculation of cement content	This was calculated using the value of mixing water content and the water/cement ratio. Thus, it was required 565 kg per m ³ of concrete.
(viii) Estimation of aggregate proportions	They were determined using a graphical method. The recommended value is 52% for fine aggregate and 48% for coarse aggregate.
(ix) Adjustment of water content	Due to aggregate moisture, this was performed assuming a volume of the concrete mixture of 0.033 m ³ to perform a test for one slump and two beams. Moisture was determined for both coarse and fine aggregates.

3.4. Evaluation of Mechanical Properties

Flexural and compression resistance tests were carried out at 28 days of the age of beams and cylinders with different contents of recycled aggregates to evaluate the concrete's mechanical properties (Tables 5 and 6). In terms of flexural strength, it was observed that compared to the reference sample (M1), made with aggregates of natural origin and considering the minimum strength required for paving stones (5 MPa), the mixtures M2, M3 and M4 met with established mechanical requirements. However, given the high deviation found for the M3 mixture and the low average compressive strength, it was not considered suitable in this project. Considering the above, M2 and M4 mixtures,

which replace 50% of the fine natural aggregates and 50% of the natural coarse aggregates, respectively, were the only viable options in terms of flexural strength. On the other hand, in terms of compressive strength, mixtures M2 and M4 met with the established design resistance (50MPa) and are comparable to the reference mixture (M1) resistance that used fine and coarse aggregates of natural origin.

Table 5. Summary of results for flexural and compressive strength (after 28 days). Three samples for each mixture.

Mixture	Samples Flexural Strength MPa (28 Days)					Samples Compressive Strength MPa (28 Days)				
	S1	S2	S3	Average	Std Deviation	S1	S2	S3	Average	Std Deviation
M1	5.76	5.95	5.33	5.68	0.32	63.51	60.42	58.73	60.89	2.42
M2	4.00	4.60	5.11	4.57	0.56	57.43	53.68	53.34	54.82	2.27
M3	2.64	4.53	4.69	3.95	1.14	48.34	48.39	46.35	47.69	1.16
M4	5.53	4.70	4.95	5.06	0.43	55.33	56.16	56.83	56.10	0.75
M5	4.28	3.95	3.71	3.98	0.29	42.60	42.00	43.24	42.61	0.62
M6	3.16	3.84	4.41	3.80	0.63	39.69	39.25	38.77	39.24	0.46
M7	4.74	3.96	3.82	4.17	0.50	42.26	44.30	42.57	43.04	1.10
M8	4.04	4.47	3.99	4.17	0.26	37.41	42.51	42.01	40.64	2.81
M9	2.79	3.56	3.29	3.21	0.39	39.08	37.71	35.96	37.58	1.56

Table 6. Summary of results by coarse and fine aggregate combination.

		Avg Flexural Strength MPa			Avg Compressive Strength MPa			
		Fine Aggregate Replacement			Fine Aggregate Replacement			
		0%	50%	100%				
		0%	50%	100%	0%	50%	100%	
Coarse aggregate replacement	0%	5.68	4.57	3.95	0%	60.89	54.82	47.69
	50%	5.06	3.98	3.80	50%	56.10	42.61	39.24
	100%	4.17	4.17	3.21	100%	43.04	40.64	37.58

Figure 4 summarizes the results obtained for flexural and compressive tests, while Figure 5 shows the relationship between flexural and compressive strengths obtained from mechanical tests for all nine specimens.

Finally, when analyzing the correlation between compressive and flexural strength of the results (Figure 5), it was observed that flexural strength represented between 8 and 10% of the compressive strength, such output is similar to the relationship that conventional concrete offers (using natural aggregates).

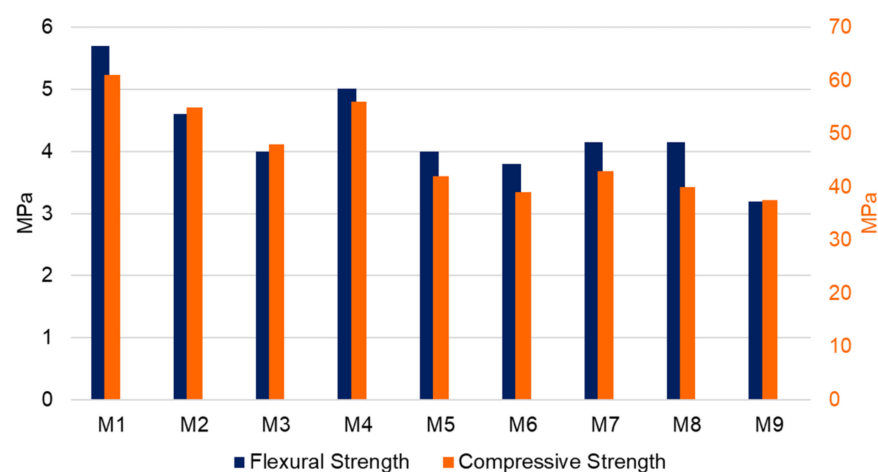


Figure 4. Mechanical properties of concrete mixtures: flexural strength, compressive strength.

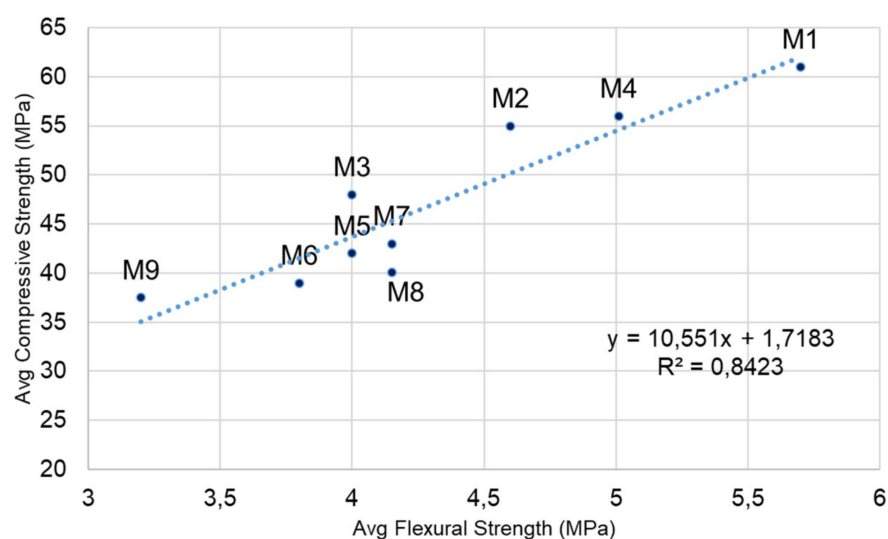


Figure 5. Compressive and flexural strength of concrete mixtures.

3.5. Performance-Based Selection of Mixture

The M2 (50% replacement of fine natural aggregate) and M4 (50% replacement of natural coarse aggregate by recycling) mixtures were selected based on results for flexural (modulus of rupture) and compressive strengths of the concrete mixtures concerning the behavior of the reference mixture and the established design strengths. Figure 6 shows the new paving stones from the M2 mixture, and Table 7 summarizes the most relevant parameters for selected mixtures (M2 and M4) compared to the reference sample M1.



Figure 6. Paving stones made from M2 concrete mix using recycled aggregates.

Table 7. Parameters for selected mixtures (M1, M2, and M4).

Parameters (Avg Values)		Mix		
		M1	M2	M4
Dimensions (cm)	Length	20.45	20.35	20.3
	Width	15.35	15.25	15.25
	Height	10.20	10.05	10.05
% of absorption		3.9	8.6	8.6
Std deviation		0.67	0.87	0.73
Wear (mm)		13.9	12.3	19.2
Std deviation		0.28	0.14	0.99
Flexural strength (MPa)		9.4	4.45	4.2

4. Discussion

4.1. Physical, Chemical and Mechanical Characterization

According to granulometric measurements, coarse and fine aggregates did not fully satisfy the reference standard (NTC 174). However, these aggregates were used in this study due to their high quality and commercial acceptance (mechanical properties and durability). For recycled aggregates, these satisfy acceptance ranges according to the reference standard (NTC 174). Except for the finest fraction of coarse aggregates (fringe sieve between #200 and #10). Thus, fine recycled aggregate is higher than the fine aggregate while maintaining the same maximum size regarding fineness modulus.

It is observed from the fineness modules that the recycled fine aggregate is higher than the natural one, while the maximum sizes for both types of aggregates are equal. This indicates that concrete with recycled aggregates may require higher water content to achieve workabilities, similar to conventional concrete. Regarding other interest parameters, it was possible to identify several important differences between recycled and virgin aggregates. In the case of absorption and density, recycled aggregates provided values 9 to 11 times higher and 32 to 35% lower than natural ones. Recycled aggregates have a lower density or specific gravity concerning the densities of natural aggregates. Thus, commonly the water content required for a concrete mix with the same workability is higher when recycled aggregates are used and may also be worsened; this is because although in this case the standards are met, the elongation and flattening index of recycled coarse aggregates is relatively low compared to natural ones [44].

Another interesting difference is related to mechanical properties, demonstrating that recycled aggregates proved three times less resistant to wear than natural aggregates (64% of loss). Lastly, unitary mass for both recycled and natural aggregates presented conventional values for concretes (950 to 1950 kg/m³). Thus, both aggregate materials can reduce cement consumption, plastic deformation and contribute to concrete density once it is solidified. In terms of chemical properties, it was found that despite organic material not affecting the hydration of Portland cement, virgin fine aggregates (sand) provide a higher content compared to recycled ones. This can be explained by the fact that natural aggregates come directly from the mineral quarry. Regarding wear resistance under exposition to sodium sulfate, values of 68% and 86% were registered for recycled coarse and fine aggregates, respectively.

4.2. Mechanical Evaluation

According to Figure 4, when 50% fine aggregate is replaced, the flexural strength is reduced by approximately 20%. In contrast, with the replacement of the coarse aggregate, a reduction of 10% is presented concerning the reference mixture, noting that it gets better bending behavior of the mix when replacing coarse aggregates. Regarding mixtures with a 100% replacement in both fine and coarse, the resistance decreased by approximately 30% and did not satisfy the NTC 2017 standard (4.2 MPa). On the other hand, it is observed that when replacing 50% of the coarse aggregate, the resistance to compression is reduced by approximately 8%. It is a concrete that met the established mechanical requirements; by replacing 100% of the coarse aggregate, the compressive strength is decreased by approximately 30%. Therefore, this replacement was not considered viable due to its high reduction in mechanical performance.

When combining the recycled aggregate replacements between fine and coarse, a decrease of more than 30% and 25% of the mechanical resistance to compression and flexion, respectively, values that do not meet the initial requirement. Reductions of this concrete's mechanical properties are mainly since recycled materials from paving stones provided high absorptions greater than 14%, indirectly indicating that the aggregates also offered high porosity, which implied a considerable volume of voids in the internal structure of the aggregates. In addition, the pores of recycled material include small cracks that, within the concrete, reduce the mechanical properties of mixtures. Although there are different improvement techniques for the mechanical response (e.g., coatings and

mineral fillers), the most economical and straightforward way is balancing the mechanical properties with the partial use of natural aggregates. In addition to the environmental benefits of using recycled aggregates, these have better adherence to the matrix, low content of organic matter, and typically low cost. Finally, by replacing 50% of fine natural aggregate with recycled aggregate, it was possible to observe a reduction in compressive strength by approximately 10%, a similar value to replacing 50% of coarse aggregate in the mix. One hundred percent replacement of the fine aggregate content decreases resistance by approximately 20%, which was an admissible value according to the requirement. Nevertheless, mechanical behavior in terms of flexure was less than 4.2 MPa. Therefore, the M7 mixture was not considered for the manufacture of paving stones.

According to Figure 4, mixes M2, M3, and M4 met the mechanical requirements established regarding flexural strength. However, given the high deviation found for the M3 mixture and the low average compressive strength, this study was not considered. Therefore, the M2 and M4 mixtures, which replace 50% of the fine natural aggregates and 50% natural coarse aggregates, respectively, were the two only viable options for flexural strength fulfillment.

4.3. Properties of Selected Mixes

Average values for absorption mixtures M2 and M4 are higher than 7%, while the M1 mixture is within the parameter according to the NTC 176 standard [45], which is to be expected taking into account that M2 and M4 mixtures contain recycled material from old paving stones, which are more porous and less dense. In terms of wear, it must be less than 23 mm, according to the NTC 5147 standard [46]. Tested mixtures showed satisfactory results since all of them satisfy that reference parameter. However, it is noteworthy that new paving stones with M2 concrete presented lower wear than M1, contrary to the M4 sample that presented higher wear. Fifty percent replacement of fine aggregates in M2 did not affect the wear of the new paving stone, which indicates that the manufacture of paving stones with such a mixture will promote durability by friction over time. New paving stones made with recycled material decreased their resistance by approximately 50% compared to M1. This decrease due to the recycled material used is highly porous and has possible microcracks derived from the crushing process.

To summarize, it is observed that new paving stones manufactured with a 50% replacement of natural fine and coarse aggregates by recycled aggregates (M2 and M4) satisfactorily comply with the minimum mechanical resistance (4.2 MPa according to the NTC 2017 standard). However, the results in absorption and wear are above the permitted values for these applications. It is recommended to quantify in future research the practical impact on the lifecycle of paving stones, including the interaction between these high percentages of absorption and wear. The results obtained demonstrated that it is possible to fabricate paving stones with similar properties to those fabricated using 100% virgin material. Possible applications of concrete with recycled aggregates include structural applications and buildings, however, it is necessary to perform specific experiments to validate its suitability in such applications. The study summarized in this article did not consider extreme conditions such as exposure to fire or freezing environment.

4.4. Limitations of the Study

The experimentation and examination processes followed in this study involved several characterization, physical and chemical analysis, and laboratory tests. Therefore it is relevant to address several limitations regarding the methodology, materials and results obtained:

- Properties of raw material for aggregates (old paving stones) can vary depending on the age, degree of wear and typical use conditions. Hence, it is possible to find differences in results for mechanical properties considering another paving stone with different age and use regime.

- Results of mechanical properties obtained are valid for the aggregate sizes considered in this study. The use of high-technology jaw crushers can play an important role to analyze smaller sizes of aggregate and their influence on mechanical properties and durability of the new recycled material.
- Environmental conditions (humidity and temperature) were not controlled or measured during the development of experiments. Possible differences in results can be observed in regions with colder or hotter weather. Mechanical test were performed in cold conditions only. Therefore, results can vary under other conditions not considered in this study (i.e., mechanical behavior after exposition to fire).
- Characterization processes (density, consistency, absorption, chemical properties, and mechanical wear) followed NTC (Colombian technical standards). Such standards are conventional based on ASTM standards, although methodological differences are not ruled out compared to another standard or newest versions of the ASTM standards.

5. Conclusions

This article described first the evaluation of the mechanical properties of concrete using recycled aggregates obtained from old paving stones, and second the development of two suitable concrete mixtures for manufacturing new paving stones with important replacements of the fraction of natural coarse and fine aggregate. Based on the technical standards, the two concrete mixes with the replacement of 50% by weight of the fine and coarse fraction of natural origin presented adequate flexural strength when evaluated as new paving stones. These results are entirely satisfactory concerning the replacements found in the literature where recycled aggregates are typically used in fractions less than 50% by weight of the natural coarse or fine aggregates of a concrete mix. This is fundamentally due to the high quality and processing of the recycled aggregates used in this project. It is remarkable that the selected recycled aggregates were fundamentally constituted of concrete and did not present significant contamination.

On the other hand, in terms of the relative high absorption and low resistance to wear of the paving stones developed, future research is proposed to improve recycled aggregates against these variables, particularly wear caused by pedestrian. The correlation of existing standardized wear tests with actual applications still demands better approaches that open the possibility of using recycled aggregates without affecting construction safety. Finally, this study demonstrated that use of recycled aggregates has the potential to reduce the environmental impact and, when applied correctly, it can significantly reduce the costs of a construction project. Therefore, results from this project, together with more research results about recycling technology in building materials are the base of a circular economic model proposed for one of the major cities from Colombia, Santiago de Cali (Figure 7). In particular, the Circular Economy Model, a tool led by the municipal planning department of the mayor's office of Santiago de Cali for the construction sector, is composed of four stages that are: (I) production of construction materials, (II) construction, (III) use and operation and (IV) termination of the life cycle of buildings and infrastructure. It also includes the articulation with other productive sectors that generate waste of interest to the construction chain, a strategy known as industrial symbiosis. Furthermore, in the Circular Economy Model, it is very important to connect at all stages with the Environmental and Technological Park (Parque Ambiental y Tecnológico) of Santiago de Cali, a place conceived as a physical space that has infrastructure and shared human capital that reserves investment for sustainable construction companies. As they are inserted in flexible groups, they find support (in situ and in the park) to transform C&DW and other waste into sustainable materials for construction.

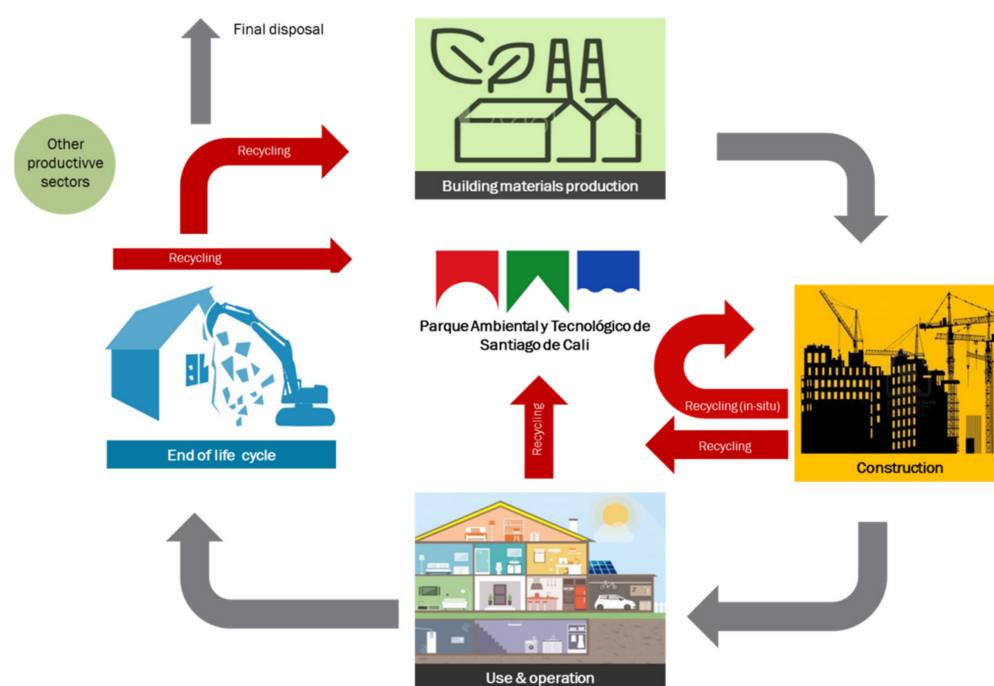


Figure 7. Circular Economy Model for the construction sector of Santiago de Cali which is composed of the phases of production of construction materials, construction, use and operation, and completion of the life cycle of buildings and infrastructure.

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Appendix A. Equivalence between NTC, INV and ASTM Standards

Table A1. Equivalence between NTC, INV and ASTM standards.

NTC/INV Standard (Colombia)	Equivalent International Standard
NTC 174	ASTM C1231
INV E-500	—
INV E-307	—
INV E-310	—
NTC 7707	ASTM C136
INV E-213	—
NTC 237	ASTM C128
INV E-222	—
NTC 176	ASTM C127
INV E-223	—
NTC 92	ASTM C29

Table A1. Cont.

NTC/INV Standard (Colombia)	Equivalent International Standard
INV E-217	–
INV E-230	–
NTC 126-206	ASTM C88
INV 3-220	–
NTC 127	ASTM C40
NTC 98	ASTM C131
INV E-219	–
NTC 2017	–
INV E-402	–
NTC 673	ASTM C42
INV E-414	–

Appendix B. Additional Properties of Aggregates and Quantities for Experimental Mixtures

Table A2. Granulometry of recycled aggregate samples (using sieve).

Sizes		Weight and Grade of Samples						
Passing Size	Detained Size	A	B	C	D	E	F	G
3"	2 1/2"					2500		
2 1/2"	2"					2500		
2"	1 1/2"					5000	5000	5000
1 1/2"	1"	1250					5000	5000
1"	3/4"	1250						
3/4"	1/2"	1250	2500					
1/2"	3/8"	1250	2500					
3/8"	1/4"			2500				
1/4"	N°4			2500				
N°4	N°8				5000			
Number of balls		12	11	8	6	12	12	12
Angular speed (RPM)		500	500	500	500	1000	1000	1000

Table A3. Dry weight and absolute volume of components per cubic meter of concrete.

Component	Dry Weight Kg/m ³	Apparent Density g/cm ³	Absolute Volume L/m ³	Proportion
Cement	565	3.1	182	1
Water	203.8	1	203.8	0.36
Air content	–	–	0	0
Coarse aggregate	809.44	2.81	288	1.43
Fine aggregate	876.89	2.68	326.2	1.55
Total	2455		1000	

Table A4. Moisture content for natural aggregates.

Parameter	Fine Aggregate	Coarse Aggregate
Initial weight (g)	381.9	327.7
Dry weight (g)	349.2	315.9
Water content (g)	32.7	11.8
Moisture (%)	8.57	3.60

Table A5. Density and absorption for natural aggregates.

Parameter	Fine Aggregate	Coarse Aggregate
Nominal density (g/cm ³) at 23 °C	2.80	2.93
Apparent density (g/cm ³) at 23 °C	2.68	2.81
Relative density (g/cm ³) at 23 °C	2.72	2.85
Absorption (%)	1.6%	1.4%

References

- Yang, D.; Liu, M.; Ma, Z. Properties of the foam concrete containing waste brick powder derived from construction and demolition waste. *J. Build. Eng.* **2020**, *32*, 101509. [\[CrossRef\]](#)
- John, V. Recycling of rubble for the production of building materials. In *Use of Waste as Construction Materials*; EDUFBA: Salvador, Brazil, 2001; Volume 312, pp. 27–45.
- Terry, M. Waste Minimization in the Construction and Demolition Industry. Bachelor's Thesis, Civil & Environmental Engineering, University of Technology, Sydney, NSW, Australia, 2004.
- Shen, L.; Tam, V.W. Implementation of environmental management in the Hong Kong construction industry. *Int. J. Proj. Manag.* **2002**, *20*, 535–543. [\[CrossRef\]](#)
- Francisco, J.T.M.; De Souza, A.E.; Teixeira, S.R. Construction and demolition waste in concrete: Property of pre-molded parts for paving. *Cerâmica* **2019**, *65*, 22–26. [\[CrossRef\]](#)
- Galán, B.; Viguri, J.; Cifrian, E.; Dosal, E.; Andres, A. Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants. *J. Clean. Prod.* **2019**, *236*, 117523. [\[CrossRef\]](#)
- Kartam, N.; Al-Mutairi, N.; Al-Ghusain, I.; Al-Humoud, J. Environmental management of construction and demolition waste in Kuwait. *Waste Manag.* **2004**, *24*, 1049–1059. [\[CrossRef\]](#) [\[PubMed\]](#)
- Lederer, J.; Gassner, A.; Kleemann, F.; Fellner, J. Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: A case study from Vienna. *Resour. Conserv. Recycl.* **2020**, *161*, 104942. [\[CrossRef\]](#)
- Juan-Valdés, A.; García-González, J.; Rodríguez-Robles, D.; Guerra-Romero, M.I.; López Gayarre, F.; De Belie, N.; Morán-del Pozo, J.M. Paving with Precast Concrete Made with Recycled Mixed Ceramic Aggregates: A Viable Technical Option for the Valorization of Construction and Demolition Wastes (CDW). *Materials* **2019**, *12*, 24. [\[CrossRef\]](#)
- Whittaker, M.J.; Grigoriadis, K.; Soutsos, M.; Sha, W.; Klinge, A.; Paganoni, S.; Casado, M.; Brander, L.; Mousavi, M.; Scullin, M.; et al. Novel construction and demolition waste (CDW) treatment and uses to maximize reuse and recycling. *Adv. Build. Energy Res.* **2019**, 1–18. [\[CrossRef\]](#)
- Cantero, B.; Bravo, M.; de Brito, J.; del Bosque, I.S.; Medina, C. Mechanical behaviour of structural concrete with ground recycled concrete cement and mixed recycled aggregate. *J. Clean. Prod.* **2020**, *275*, 122913. [\[CrossRef\]](#)
- Chen, A.; Han, X.; Chen, M.; Wang, X.; Wang, Z.; Guo, T. Mechanical and stress-strain behavior of basalt fiber reinforced rubberized recycled coarse aggregate concrete. *Constr. Build. Mater.* **2020**, *260*, 119888. [\[CrossRef\]](#)
- De Andrade, G.P.; Polisseni, G.D.C.; Pepe, M.; Filho, R.D.T. Design of structural concrete mixtures containing fine recycled concrete aggregate using packing model. *Constr. Build. Mater.* **2020**, *252*, 119091. [\[CrossRef\]](#)
- Botero, L. *Sostenibilidad de la Disposición de Escombros de Construcción y Demolición en Bogotá*; Universidad de Los Andes: Bogotá, Colombia, 2003.
- Pérez, J. *Estudio del Potencial de Reciclaje de Desechos de Materiales de Construcción y Demolición en Santa Fé de Bogotá*; Universidad de Los Andes: Bogotá, Colombia, 1996.
- Poon, C.S.; Chan, D. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Constr. Build. Mater.* **2006**, *20*, 578–585. [\[CrossRef\]](#)
- Bazaz, J.; Khayati, M.; Akrami, N. *Performance of Concrete Produced with Crushed Bricks as the Coarse and Fine Aggregate*; The Geological Society of London: London, UK, 2006; p. 10.
- Wong, Y.D.; Sun, D.D.; Lai, D. Value-added utilisation of recycled concrete in hot-mix asphalt. *Waste Manag.* **2007**, *27*, 294–301. [\[CrossRef\]](#) [\[PubMed\]](#)
- Agrela, F.; Barbudo, A.; Ramírez, A.; Ayuso, J.; Carvajal, M.D.; Jiménez, J.R. Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. *Resour. Conserv. Recycl.* **2012**, *58*, 98–106. [\[CrossRef\]](#)
- Pérez-Benedicto, J.A.; del Río-Merino, M.; Peralta-Canudo, J.L.; de la Rosa-La Mata, M. Mechanical characteristics of concrete with recycled aggregates coming from prefabricated discarded units. *Mater. Construcción* **2012**, *62*, 25–37. [\[CrossRef\]](#)
- Çakır, Ö.; Dilbas, H. Durability properties of treated recycled aggregate concrete: Effect of optimized ball mill method. *Constr. Build. Mater.* **2021**, *268*, 121776. [\[CrossRef\]](#)
- Vedrtam, A.; Bedon, C.; Barluenga, G. Study on the Compressive Behaviour of Sustainable Cement-Based Composites Under One-Hour of Direct Flame Exposure. *Sustainability* **2020**, *12*, 10548. [\[CrossRef\]](#)
- Zareei, S.A.; Ameri, F.; Bahrami, N.; Shoaee, P.; Musaei, H.R.; Nurian, F. Green high strength concrete containing recycled waste ceramic aggregates and waste carpet fibers: Mechanical, durability, and microstructural properties. *J. Build. Eng.* **2019**, *26*, 100914. [\[CrossRef\]](#)

24. Zahid-Hossain, F.; Shahjalal, M.; Islam, K.; Alam, M.T.y.M.S. Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber. *Constr. Build. Mater.* **2019**, *225*, 983–996. [[CrossRef](#)]
25. Alam, M.S.; Slater, E.; Billah, A.H.M.M. Green Concrete Made with RCA and FRP Scrap Aggregate: Fresh and Hardened Properties. *J. Mater. Civ. Eng.* **2013**, *25*, 1783–1794. [[CrossRef](#)]
26. Meherier, M. *Investigation of Mechanical and Durability Properties of Cement Mortar and Concrete with Varying Replacement Levels of Crumb Rubber as fine Aggregate*; University of British Columbia Okanagan: Kelowna, BC, Canada, 2016.
27. Limbachiya, M.; Leelawaty, T.; Dhir, R. Use of recycled concrete aggregate in high-strength concrete. *Mater. Struct.* **2000**, *33*, 574. [[CrossRef](#)]
28. Tiempo, E.I. *Estación de Transferencia EDT Carrera 50 en Santiago de Cali. Problemáticas Asociadas a la Disposición Inadecuada de los RCD*; El Tiempo: Bogotá, Colombia, 2018.
29. Pais, E.I. *Residuos de Construcción Dispuestos Inadecuadamente en el Rio Cauca*; El País: Bogotá, Colombia, 2014.
30. Tiempo, E.I. *Extracción de Roca en el Rio Pance*; El Tiempo: Bogotá, Colombia, 2018.
31. Gobernación del Valle. *Areneros del Rio Cauca Buscan Formalizar su Actividad ante la CVC y el Ministerio de Minas*; Gobernación del Valle: Valle del Cauca, Colombia, 2017.
32. Ministry of Environment and Sustainable Development. *Resolution 472*; Ministry of Environment and Sustainable Development: Bogotá, Colombia, 2017.
33. Bedoya-Montoya, C. *El Concreto Reciclado con Escombros Como Generador de Hábitats Urbanos Sostenibles*; Universidad Nacional de Colombia: Medellín, Colombia, 2003.
34. National Administrative Department of Statistics—DANE. *First Report on Circular Economy*; Government of Colombia: Bogotá, Colombia, 2020.
35. Oliveira, T.C.; Dezen, B.G.; Possan, E. Use of concrete fine fraction waste as a replacement of Portland cement. *J. Clean. Prod.* **2020**, *273*, 123126. [[CrossRef](#)]
36. Diosa, J.S. *Experimental Analysis of the Mechanical Properties of High-Strength Concrete Made with Recycled Concrete Aggregates*; Pontificia Universidad Javeriana Cali: Cali, Colombia, 2020.
37. Hurtado, I. *Evaluation of the Effect of the Partial Replacement of Portland Cement by Ash from the Paper Industry in Mortars and Walls*; Pontificia Universidad Javeriana Cali: Cali, Colombia, 2019.
38. Londoño, J. *Mechanical Behavior of Precast Concrete Elements with Recycled Aggregates within the Source that Generates Them*; Pontificia Universidad Javeriana Cali: Cali, Colombia, 2016.
39. Wagih, A.M.; El-Karmoty, H.Z.; Ebid, M.; Okba, S.H. Recycled construction and demolition concrete waste as aggregate for structural concrete. *HBRC J.* **2013**, *9*, 193–200. [[CrossRef](#)]
40. Zhang, C.; Hu, M.; Yang, X.; Miranda-Xicotencatl, B.; Sprecher, B.; Di Maio, F.; Zhong, X.; Tukker, A. Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. *J. Clean. Prod.* **2020**, *266*, 121718. [[CrossRef](#)]
41. ICONTEC. *NTC 174:2018 Concrete. Specifications for Concrete Aggregates*; ICONTEC: Bogotá, Colombia, 2004.
42. Sanchez De Guzmán, D. *Tecnología del Concreto Y del Mortero*; Bhandar Editores: Bogotá, Colombia, 2001.
43. ICONTEC. *NTC 2017:2018 Pavers of Concrete for Pavement*; ICONTEC: Bogotá, Colombia, 2018.
44. Pacheco-Torgal, F.; Jalali, S.; Labrincha, J.; John, V. *Eco-Efficient Concrete*; Woodhead Publishing Limited: Oxford, UK; Cambridge, UK; Philadelphia, PA, USA; New Delhi, India, 2013.
45. ICONTEC. *NTC 176:2019 Method to Determine the Relative Density and Absorption of Coarse Aggregate*; ICONTEC: Bogotá, Colombia, 2019.
46. ICONTEC. *NTC 5147:2002 Test Method for Determining Abrasion Resistance of Floor and Pavement Materials by Sand and Wide Wheel*; ICONTEC: Bogotá, Colombia, 2002.