Technical and Economic Feasibility of Ceramic Waste as a Coarse Concrete Aggregate.

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Abstract

The production of solid waste continues to increment over the world. In Colombia waste generation grew 13% in only 6 years. This has led to a sanitary landfill crisis in various municipalities, like Medellín, where its main landfill *La Pradera* has only 7 years of lifespan and no current backup plan. This has created a massive necessity for alternative ways to waste reutilization and development into a circular economy. One of the industries present in the *Valle de Aburrá* is GAMMA, a ceramic insulator producer, for which approximately 10% of the monthly production is waste. Ceramic waste can be very harmful to the environment causing high concentration of Magnesium or Iron in the soil, also its degradation can take thousands of years.

The infrastructure sector is one of the main factors in the economy, where concrete is a raw material with a great potential for residue reutilization. Eco-efficient concretes made from ceramic waste have been studied and shown to be compliant regarding compressive resistance demanded by standards (BS EN 12390-6:2001) [1]. In this study, ceramic electrical insulators are used as a coarse aggregate in concrete manufacturing for different substitution percentages of coarse aggregate (0%, 25%, 50%, 75% and 100%). Our results confirm the performance potential and the economic viability of the material for the proposed scenarios when compared to conventional concrete. The 25% of coarse aggregate replacement was the only mixture compliant with Colombian standards having an average compressive resistance of 28.05 MPa after 28-day of setting. For both the modified and conventional concrete, the workability results were 7cm within the required range of 2,5 and 7,5cm for structural concrete.

1. Introduction

Throughout history the activities carried out by humans have generated waste and for a long time this was not a matter of concern for the communities. This fact becomes an issue since in recent years the production of waste has increased significantly [2]. In Colombia we are not oblivious to this problem, as in 2008, 9.1 million tons of solid waste were transported daily to landfills [2]. Only in 2016 there was already an increase to 11,315,000 tons disposed daily. Colombia has shown a 13% increase waste generation, between 2010 and 2016 even though the increase in the population was for that period of time 7% [3]. Individually La Pradera Landfill at Medellín, serving the metropolitan area of Valle de Aburrá, received 2.5 million tons of waste in 2017 [4]. Because of this, it is estimated that La Pradera landfill lifespan was reduced to seven years with no contingency plan as the estimation of the lifespan for sanitary landfills of nearby regions are close to running out of capacity. [3]

In *Medellín* 68% of waste transported to landfills comes from households, [5] and even though the city has seen a shift from the industrial sector to the service industry [6], this sector still generates 10% of the waste. One of the industries in the metropolitan area of the *Valle de Aburrá* is the ceramic industry, that generates a large amount of waste harmful to the environment, since it not only contributes to the sanitary landfills crisis, but also impacts negatively environment because these wastes leach manganese, calcium, iron, nickel and magnesium in the soil affecting fertility or the composition of the vegetation that might grow in the future around the affected area [7].

One of the possible uses for ceramic breakage residues is its incorporation as a fine or coarse aggregate in concrete [8]. This topic has been studied in several articles, and has shown positive results, but it has not been analyzed in the Colombian context regarding economic variables and technical norms that apply like NTC-174 in terms of the aggregates, NTC 1377 regarding cylinder testing and the NSR-10 which states the type of concrete and water/cement ratio and the minimal resistance required for the concrete.

There has been some research about the possibility of using ceramic in the manufacturing of concrete, as a partial substitute for cement or aggregates, demonstrating that the use of this type of concrete could be for both structural and non-structural construction [8] having physical properties as the density and workability and mechanical qualities such as compressive and tensile strength, and permeability being quite close or even better to those of conventional concrete [10], also it has been shown that recycled ceramic aggregate does not interfere with the chemical reactions which occur during cement hydration while the concrete is setting and hardening [11], other studies have found that the mineralogical composition thus diffractometric and spectroscopic techniques of ceramic waste have pozzolanic properties which can be very effective in the manufacture of concrete [12].

Currently in Medellín, the construction sector is positioned as the main driver of the economy [13]. CAMACOL (Colombian Chamber of Construction) is implementing a plan to increase the demand for construction, based on three performance pillars (trust, credit channel and employment) [14]; thus adding ceramic waste to the concrete benefits both the construction industry by lowering costs and the environment by reducing waste in landfills and soil pollutants.

Therefore, the following questions arise: Is it possible within the context of the *Valle de Aburrá* to pursue a project about using ceramic waste in the manufacture of concrete, which complies with the earthquake resistance standards of Colombia? And if so, what is the optimal replacement proportion of these residues in the concrete, taking into account both resistance and economic variables?

Concrete is a mixture of Portland cement, water, sand as fine aggregate and rocks, as coarse aggregates where the proportions of these materials impact the resistance of the resulting concrete [15]. Concrete production has also been an environmental problem due to the gases and particulate materials that are produced in each of its stages, as the demand for infrastructure grows the demand concrete also increases, being the main construction material worldwide. Resulting from this problematic situation, research endeavors on pollution control and substitute alternatives to the commonly used aggregates began [16].

Concrete manufacturing with coarse aggregates with at least 20% from waste is called "green concrete" [17]. This type of concrete has been around since 1951 (DIN Standard 4163) [18], for concrete in different forms from high-volume fly ash concrete, ultra-high performance concrete, geopolymer concrete and lightweight concrete [19]. Until now, the investigations carried out on the subject reflect technical feasibility studies in North America, Europe and Asia under current standards.

Worldwide every day there is an approximate 30% of ceramic electrical insulators as waste generation, detrimental both to the production companies affecting costs [20] and to the environment, since these are nearlynon-biodegradable. As Sekar mentions in countries such as India, the use of waste does not yet reach the expected level, but many of these wastes are being studied for use as aggregates or as a partial replacement for concrete ingredients [17].

The demand for green concrete has increased due to regulations for construction projects where the reduction of the carbon footprint is sought [19] to approach a sustainable construction. This requires certifications such as EDGE (Excellence in Design for Greater Efficiencie) and LEED (Leadership in Energy and Environmental Design), implemented in countries such as Canada, China, India, Mexico, and Colombia. [21].

Research on green concrete is extensive with various residues added. Coarse aggregate replacement in concrete is currently implemented in Colombia, though in a very empirical manner, but aiming to fulfill NSR 10, NTC 174 and NTC 1377 standards. In this project we seek to show how replacing coarse aggregate in a model concrete formulation by ceramic waste, affects concrete´s performance and physical properties per concrete´s standards.

2. Experimental

Concrete consists of cement, water, coarse and fine aggregates. In this case the idea was to reformulate a concrete model formulation by replacing conventional coarse aggregate with ceramic waste at different percentages by weight ranging from 0% to 100% following Colombian standards for concrete making and testing.

Materials

Argos Type 1, Ordinary Portland Cement (OPC) was obtained from a local construction retailer, Homecenter. Fine and coarse aggregates (sand and gravel) were obtained from Homecenter and sieved to determine and classify particle size distribution following the NTC-77 standard (see table 1). In terms of density and absorption the NTC 176 and 237 standards (Table 1) were followed and the humidity percentage following the NTC 1776 (see Table 1). Electrical ceramic insulator waste was obtained from GAMMA and crushed with a Blake Jaw Crusher, to determine particle size distribution, humidity, absorption and density with the same standards mentioned before and make it suitable as coarse aggregate replacement. Lastly municipal water from Medellín was used to manufacture concrete samples.

Methods

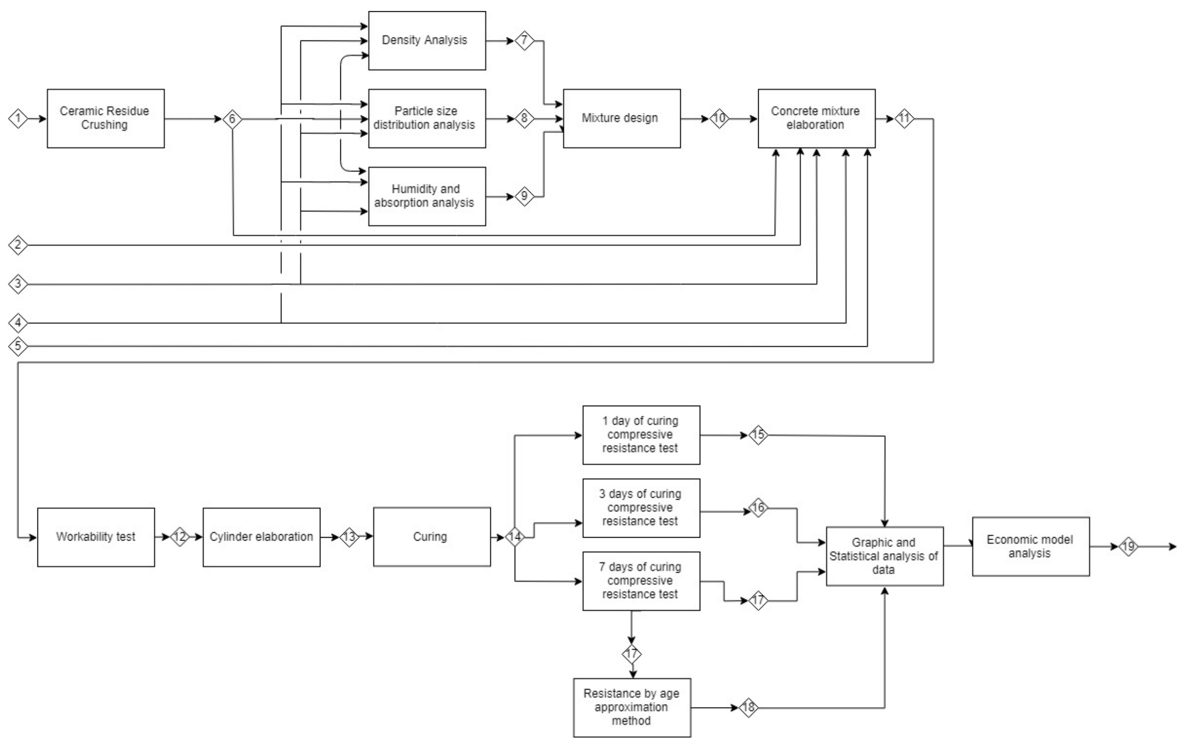

Figure 1. Block diagram of Methods

Table 1. Block diagram flows

	Flow
1	Ceramic residue
2	Cement
3	Sand

4	Gravel
5	Water
6	Crushed ceramic
7	Density results for aggregates
8	Particle size distribution results for aggregates
9	Humidity and absorption results for aggregates
10	5 mixture design results
11	Concrete mixtures
12	Workability results and mixture suitable for cylinders
13	Cylinders of concrete
14	Cured cylinders
15	Compressive resistance results for 1 day cylinders curing
16	Compressive resistance results for 3 day cylinders curing
17	Compressive resistance results for 7 day cylinders curing
18	Approximate compressive resistance results for 28 day cylinders curing
19	Economic Model results

Following the Colombian earthquake resistance standard (NSR-10), based on the conditions shown we sought to elaborate a C1 concrete, meaning it is exposed to normal humidity and no chlorides this being because we aimed at residential building construction to be the final use of the material. According to NSR-10, the minimum resistance for the concrete must be 17Mpa with an error factor of ± 7Mpa, meaning that the design resistance used was 25 Mpa.

A technical norm for the preparation and curing of concrete specimens for laboratory tests, the NTC 1377, states that the molds must be made from steel, iron or any material not absorbent with the possibility of reacting to the concrete. Once the concrete mixture is made and properly mixed, when placed into the cylinders is best to add mineral oil to the mold to avoid sticking and must dry in a vertical manner. The molds used in this case were 10cm in diameter and 20 in height.

Before producing any mixture, the ceramic waste was crushed in a Blake jaw crusher in order to reduce the particle size to a similar size of the gravel. After that procedure both the gravel and the ceramic were sifted to determine particle size distribution following the neccesary quantities according to the NTC-129. According to the specifications of concrete aggregates norm, the NTC-174 and the NTC 77, the fineness modulus was determined and later used for the mixture design.

In the NRS-10 the resistance result must be acquired by the average between at least 2 test cylinders, but in the NTC 1377 is stated that for better results, 3 cylinders for each age of curing (1, 3, 7 and 28 days) for each mixture should be made. The aim was to replace as much percentage as possible of gravel to maximize the use of the ceramic waste and reduce costs, so 4 different mixtures with a 0, 25, 50, 75 and 100% replacement will be produced.

To produce concrete mixture, the rodded dry unit mass of the aggregates must be determined for the mixture desing following de ACI 211.1. When all the steps mentioned before following the NTC 176 and NTC 237 are done, the process of making the test cylinders begins by mixing the water, cement, and fine aggregate, finishing with the percentages of grave and ceramic established before as the coarse aggregate.

For the mixture, according to the NTC 1377, initially the cement and fine aggregate must me rigorously mixed, the coarse aggregates are added until mixed homogenously. Later the water is added and mixed fully until desired consistency is obtained. The next step is to fill the cylinder molds and do the workability test.

The workability or slump test consists in introducing the concrete into a conic mold to see how much the concrete changes its shape. This technique has been standardized in the norm for NTC-396, and the test were performed according to this standard. Lastly the concrete cylinders dried for 24 hours and then placed in water filled tanks for curing. 3 cylinders of each mixture were removed from curing after 1 day and then submitted to a test of resistance to rupture by compression, then another 3 are removed after 3 days and tested, after 7 days another 3 for each mixture are tested and to finish with the remaining cylinders to be tested after 28 days of curing.

After the day 1, 3 and 7 results are obtained, an approximaion method is used to estimate the resistance of the concrete especimens after 28 days, taking into account that the evolution of concrete resistance cites that after 7 days the concrete has developed between 60 and 65% of its final resistance [22] [23]. For this case a 65% of developed resistance scenario was used seeking a conservative approach, concluding this the results are analyzed to determine initially, following the NTC-2275 and the NSR-10, if the minimum resistance is obtained according to the Colombian standards and if it's acceptable to use in construction,

For the economic viability assessment, costs formulations were calculated and compared to the base case construction considering different cost scenarios, where the concrete demand was 12760 m^3. Initially no coarse aggregate is replaced by waste to obtain the base value, later the variables of paying for the ceramic transportation and crushing are considered a cost for the residue producer and the constructor alternately.

The Energy consumption when crushing 1kg of ceramic is measured with a monitoring board, to later multiply to the required quantity according to the mixture formulation. Taking into account that approximately 2 tons of ceramic residue is needed for the construction, 4 workers were added in the cost as workforce for this activity, each paid the Colombian minimum wage.

Table 2. Economic scenarios

Scenarios	Description
Scenario 1	Constructor pays for ceramic crushing and transportation
Scenario 2	Constructor pays for ceramic crushing and the ceramic waste generator pays for the transportation.
Scenario 3	Constructor pays for ceramic transportation and the ceramic waste generator pays for the crushing
Scenario 4	Ceramic waste generator pays for crushing and transportation

The base case was in San Antonio de Pereira, Antioquia. All data of distances, materials and costs for transportation where obtained directly from a local construction company and considering that the ceramic waste generator is located in Sabaneta, Antioquia. Water and Cement costs were omitted since for all scenarios the quantities, distances and prices are constant.

Table 3. Distance and price of transportation for aggregates

Material	Distance (km)	Cost ($/kg)	Transportation cost (m^3/km)
Gravel	106,3	142	35000
Sand	47,7	136	
Ceramic	48	0	

Table 4. Short Description of Colombian Standards relevant to the project

Number	Name	Description
NTC-174	Standard Specification for Concrete Aggregates	This standard establishes gradation and quality requirements for fine and coarse aggregates
NTC-77	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates	The norm explains how to determine the distribution of the particle size throught a sifting process and estabishes some requierements for the aggregates.
NTC-129	Standard Practice for Sampling Aggregates	Establishes the procesess of obtaining samples of aggregates in order to determine if they are accptable for construction.

NTC-673	Standard Test Method for Compressive Strenght of Cylindrical Concrete Specimens	It explains test method of the application of an axial compressive load to the molded cylinders a speed that is within a prescribed range until failure occurs.
NTC-1377	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory	Establishes the procedure for the elaboration and curing of concrete samples in the laboratory, under the control of the materials and conditioning.
NTC-2275	Recommended Practice for Evaluation of Strenght Test Results of Concrete	Explains how to analyze the results obtained from the compression test, how to model the data and apply stadistics.
NTC-396	Standard Test Method for Slump of Hidraulic Cement Concrete	This standard establishes the test method to determine the settlement of concrete on site and in the laboratory
NTC-1776	Standard test method for total moisture content of agreggate by drying	This standard establishes the tril method to determine the humidity percentage in a concrete aggregates
NTC-176	Standard test method for specific gravity and absorption of coarse aggregate	The method determines the density and absortion of the concrete coarse aggregates.
NTC-237	Standard test method for specific gravity and absorption of fine aggregate	The method determines the density and absortion of the concrete fine aggregates.

3. Results and discussion

Initially the ceramic waste was crushed in a Blake jaw crusher, where the energy consumption of crushing 1kg was around 0,86 and 0,96 KW, and took approximately 1 minute, resulting in a 57,6 KJ/Kg consumption taking into account that the crusher used is a small crusher with a small feeding tray having lower efficiency and taking more time than in an industrial size crusher would.

The crushed ceramic waste later underwent and particle size distribution analysis along with the gravel and sand following the NTC-77 which states the permissible quantity of retained material in each sieve, the results obtained where within the stated range indicating that the materials are suitable for concrete production. With the granulometric analysis the fineness module of the sand is calculated since is required for the formulation of the concrete mixture as well as the absorption, humidity and density or unit weight which were calculated following the NTC-1776, 176 and 237 respectively. The ACI 211.1 states that if no data is available to determine the mixture standard deviation the design compressive resistance must be the required resistance plus 7Mpa, thus the design resistance was 25Mpa, since the required in the NSR 10 is 17Mpa.

Table 5. Data used for mixture design Data taken from ACI 211.1-91 [24]

Design compressive resistance	25Mpa
w/c	0,61
Fineness Module	2,9580
Aggregate maximum nominal size	25mm
Workability	Min. 2,5cm Max 7,5cm
Coarse Aggregate percentage	0,6542
Unit weigh dry rodded Gravel	1688,988095 kg/m^3
Unit weight dry rodded Ceramic waste	1257,242063 kg/m^3
Concrete approximate mass	2380 kg/m^3

The first test that was carried out was the workability test, the desired workability for structural concrete must be between 2,5cm and 7,5cm, these results are controlled according to the quantity of water added to the mixture, all 5 mixtures made the water mas added until a workability of 7cm was obtained. This results in a change to the used water and cement ratio of the formulation, for all mixtures the water quantity was reduced.

Table 6. Composition of the mixture

Material (kg)	0%	25%	50%	75%	100%
Water formulated	3,79	3,79	3,79	3,79	3,79
Water used	3,45	3,19	3,09	3,16	3,04
Cement	6,22	6,22	6,22	6,22	6,22
w/c	0,55	0,51	0,49	0,50	0,48
Gravel	22,56	16,92	11,28	5,64	0
Sand	16,01	17,45	18,89	20,33	21,78
Ceramic	0	3,87	7,75	11,62	15,50

Table 7. Properties of the aggregates

Property	Gravel	Ceramic	Sand
Density (g/ml)	2,48	2,12	2,70
Absorption %	0,35	0,63	0,54
Humidity %	0,58	0,98	0,78

Concrete obtains its strength by the hydration of the cementitious materials, when the initial water content is high the space between the cement grains is higher generating interconnected pore structures, thus reducing the concrete strength [25], so lower water/cement ratio mixtures are expected to obtain higher compressive strength.

The compressive resistance test to the cylinders where conducted according to the NTC-673 after 1, 3 and 7 days of curing. Initially the diameters of the cylinders can differ more than 2% with each other, and the L/D relation must be more than 1.75 to prevent the use of correcting factors. Both parameters were met.

When the cylinders are cracked the type of fault generated was recorded according the same Colombian standard NTC-673 that explains the types of rupture, according to the results obtained as can be evidenced in table 9, initially most failures correspond to three types, first the number 2 that corresponds to cylinders well formed at one end with vertical fissures and cylinder badly defined at the other end, we also have the typologies 5 and 6 which describe the failure in the manufacturing process of the cylinders due to lack of impacts in their different layers or a poorly distributed load surface on the part of the machine. that is reflected in no adhered heads, this can be justified due to the lack of experience that is had at the beginning for the realization of the cylinders, being an aspect that is improved in the results of the last mixtures for the percentages of 75 % and 100% where the results show typologies of rupture such as the 2 that describes a good behavior and the typology number 3 that determines malformed cylinders due to vertical cracks in columns at both ends, this can be explained due to the high amounts of ceramic replaced by the original coarse aggregate that corresponds to the gravel, where the ceramic has an extra component such as varnish can affect negatively the level of adhesion in concrete (see figure 2); It should be noted that the typology of rupture is a qualitative characteristic that is given to the test of resistance to compression, so it depends largely on the observer and the appreciation that he wants to give according to his experience, in this case with the support of a soil laboratory technician from EAFIT University.

Figure 2. Faulted cylinder

As shown in table 9, the compressive resistance of the cylinders developed according to the expectations, as is mentioned in the literature after the third day of curing the concrete has gained the 40% of its final resistance, and at the seventh the 65%, and the results shown comply with the expected. The mixture with 25% replacement showed the highest result, surpassing the conventional concrete, followed by the 100%, 75% and 50% replacement respectively, but these results lay under the conventional concrete and the design compressive resistance, both being reasons to discard the viability of this mixtures for construction purposes.

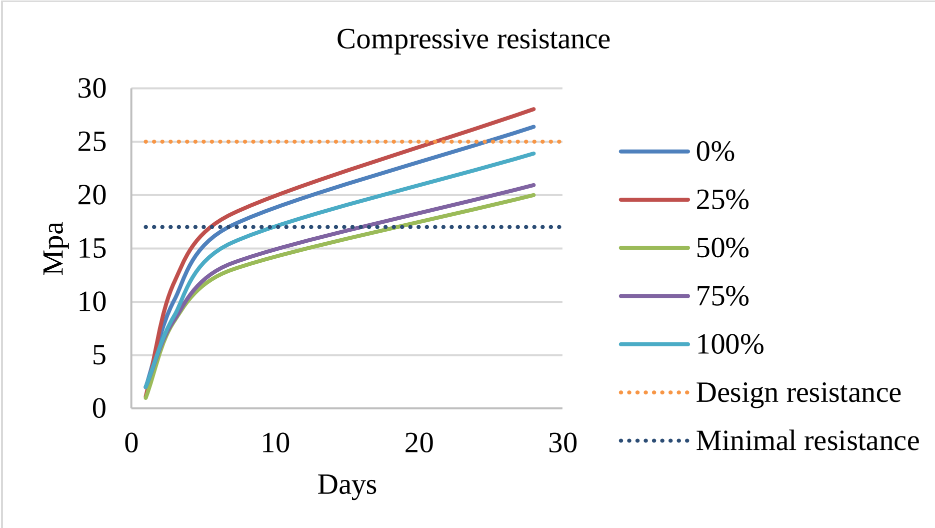

Figure 3. Compressive resistance results

An important fact to note, is that the cylinders cracked predominantly across the coarse aggregates, this can indicate that the coarse aggregates had adherence problems. This could be due to two reasons, primarily in the ceramic waste presented flat surfaces with the presence of varnish as it can be observed in the images (a) and (b) of figure 4. For the gravel purchased in a local construction retailer, it can be observed that some river stone was present, this type of aggregates has rounded edges generating possible adherence problems too.

(a) (b) (c)

Figure 4. Ceramic waste, gravel, and ceramic waste after crushing

Like mentioned before, the concrete has 65% of its final resistance after the seventh day of curing, this was used to calculate an approximate of the final compressive resistance of the test cylinders with the aim of determining viable replacement percentage that comply with the norm and apply statistical analysis. Visible in figure 3, the 0% and 25% mixtures are the only ones that surpass the design resistance of 25Mpa, leaving the

50, 75 and 100% mixtures below the expectations even if they are above the minimum resistance required by the NSR-10, 17Mpa, this makes the mixtures not viable indicating that further research is necessary if the reasoning of the results being lower of the design specifications wants to be determined.

Table 9. Compressive resistance test results

%	Day 1 (MPa)	Type of Fault	Day 3 (MPa)	Type of fault	Day 7 (MPa)	Type of fault
0	3,069	2	10,59	2	17,80	5
0	1,649	6	9,676	5	16,29	5
0	1,191	6	10,28	2	16,37	2
25	1,382	2	11,97	5	19,15	6
25	0,813	5	12,62	5	16,13	5
25	1,106	2	11,00	2	19,39	2
50	1,200	5	8,244	5	13,48	2
50	0,757	3	9,244	2	10,87	3
50	0,982	2	6,986	2	13,99	3
75	1,974	2	8,570	2	12,80	3
75	2,061	3	8,403	3	14,14	2
75	1,953	3	7,996	3	13,86	3
100	1,943	3	9,004	3	15,20	2
100	1,953	3	8,794	3	15,20	3
100	2,105	3	8,365	3	16,16	3

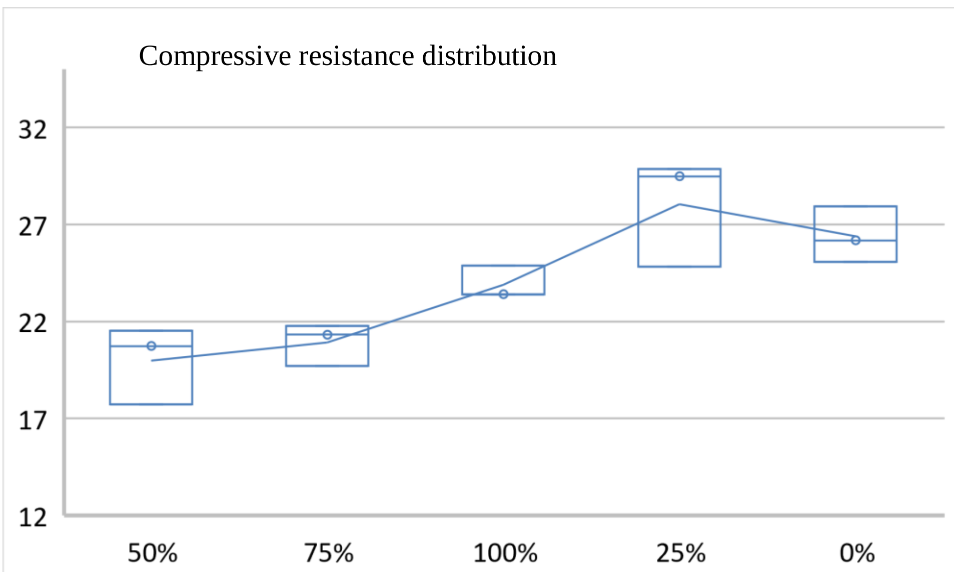

Figure 5. Distribution of resistance

The statistical evaluation of the results of the sample cylinders has the goal of determining the variability of the mixture, thus the control variables. The NSR 10 states that when the data available is limited, like in this case since only 3 cylinders per mix and age of curing were made, meaning 12 per mix the results indicate viability, but it is recommended to continue to obtain more experimental data to have more conclusive results. The statistical analysis provides a broad panorama in respect to if modifications of the mixture design are needed, the quality of the materials used and the reliability of the mixture, since the concrete homogeneity is crucial for good performance and this characteristic depends heavily on the water/cement ratio, the homogeneity of all the materials used and the fabrication and testing methods. The mixtures standard deviation must be calculated to see the variability of the mixture, if a mixture has a high standard deviation, indicates possible flaws in the construction method like improper mixing, poor compaction, delays in placement and an absence or deficiency in curing according to the NTC 2275.

Table 8. Standard deviation results for each mixture and days of curing

Standard Deviation (Mpa)				
%	**Day 1**	**Day 3**	**Day 7**	**Day 28 (approximation results)**
0	0,979	0,466	0,935	1,439
25	0,285	0,819	1,817	2,795
50	0,222	1,062	1,309	2,014
75	0,057	0,295	0,709	1,090
100	0,091	0,326	0,551	0,848

In table 8 the results of the standard deviation calculated for each mixture and each day of curing are presented. Observing the data obtained, it can be inferred that the presence of the ceramic waste produces a higher standard deviation compared to the concrete with no ceramic waste, a reason behind this could be the fact that the ceramic waste when crushed can produce very different particle shapes, depending on the initial shape of the ceramic insulator, as it can be observe on image (a) of figure 4. This can cause significant differences between the particles present in each cylinder, thus affecting the concretes homogeneity.

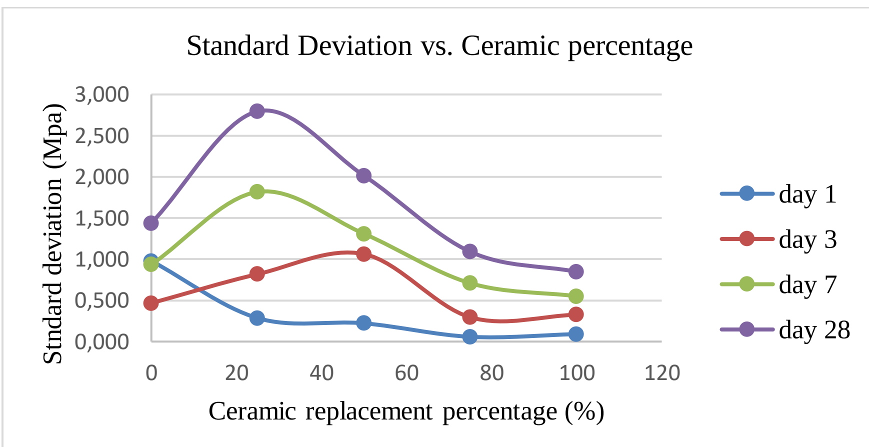

Figure 6. Variation of standard deviation according to percentages of ceramics

In Figure 6, is possible to observe how as the ceramic percentage increases the standard deviation decreases, this could be because, the mixtures where fabricated in the following order: 0%, 25%, 50%, 75% and 100%, meaning that for each mixture made, experience was gained at fabricating the cylinder specimens, like mentioned before, since the cylinders where fabricated by people with no previous experience regarding this activity. Another variable calculated was the variability coefficient, which represent the homogeneity of the result for each mixture and curing time, meaning that for grater variability coefficient the results are more heterogenic.

Table 9. Variability coefficient results for each mixture and days of curing

Variability coefficient				
%	Day 1	Day 3	Day 7	Day 28 (approximation results)
0	49,716	4,580	5,451	5,451
25	25,858	6,901	9,967	9,967
50	22,651	12,946	10,071	10,071
75	2,876	3,546	5,209	5,209
100	4,533	3,736	3,550	3,550

From the results shown in table 9, it is possible to infer that dbecause of the time spent in the curing process is more sensitive the coefficient for one day of curing have the highest values, but in order to determine the causes of variability with more certainty, according to the NTC-2275 the mixture for each replacement percentage must be made at least 10 different times.

Lastly an economic analysis was developed for 4 different possible scenarios using the 25% replacement mixture, since according to the technical analysis is the only one viable. For each scenario the concrete fabrication costs were calculated for both the modified concrete and the conventional concrete using a base case like mentioned in the experimental section, this to compare and determine economic viability of the modified concrete. The results for every scenario regarding the conventional concrete are equal since nothing is affected in the costs of the common raw materials as shown in table 10, but when it comes to the modified concrete, all of the scenarios lead to lower costs in comparison to the conventional concrete, thus giving the project economic viability even though the modified concrete requires an additional crushing process.

Table 10. Economic analysis results

Economic Scenarios Results			
Scenario	Modified concrete	Conventional concrete	Savings
1	$ 4.649.443.125	$ 4.745.809.184	$ 96.366.059
2	$ 4.648.847.011	$ 4.745.809.184	$ 96.962.173
3	$ 4.627.427.258	$ 4.745.809.184	$ 118.381.926
4	$ 4.626.831.144	$ 4.745.809.184	$ 118.978.040

4. Conclusions

All technical standards applied were satisfactorily fulfilled, from the characterization of the aggregates it was possible to reach desired properties of the materials such as density, particle size distribution, absorption percentage and humidity, contributing to the effective formulation of the mixture design for the different percentages of coarse aggregate substitution, highlighting the result of 25% of gravel replacement by ceramic waste, this being the only replacement percentage that surpassed the conventional concrete performance and complied with all the NSR-10 requirements.

The results for the 25% replacement of coarse aggregate not only complied with the norm but exceeded the requirements, leaving an open possibility for future investigations to analyze the opportunity of reducing the cement and water contents of the formulation while still fulfilling the standards thus reducing costs even further. In relation to the results shown by the 50%, 75% and 100% replacement mixtures, these results although did not meet the design criteria, did meet the minimum resistance required by the NSR-10, according to the NTC-673 in order to determine causation further research must be conducted when cylinder specimens show lower results than expected, this would make it possible to elaborate the necessary corrections to the formulation and see in what conditions these replacement percentages can be successfully carried out and explore the option of higher replacement ratios hence higher savings in raw material costs.

When the cylinders with ceramic waste presence underwent the compressive resistance test, it was noted that the adherence was one of the key issues, since the faults where located where the ceramic waste as a coarse aggregate was within the concrete. A possible reason for this to be occurring is the presence of flat surfaces in the crushed ceramic waste with varnish, it is recommended that in future research to crush the ceramic waste further to prevent the existence of the mentioned surfaces.

The variability results obtained for the different mixtures indicate the great importance that the fabrication and curing processes have within the performance of the concrete, since the homogeneity of the concrete mixture is crucial, and this property relies strongly in the experience of the person elaborating the cylinders.

All the proposed economic scenarios resulted viable, where in all cases the constructor saves money by replacing 25% of coarse aggregate by ceramic waste, even though the crushing process is added to the concrete´s production chain. This meaning that the use of ceramic waste as a replacement for the concrete´s coarse aggregate has great potential because by repurposing the ceramic waste enormous positive environmental impact is created and economically it reduces the costs of the raw materials, hence generating savings and taking into account that the efficient use of resources and circular economy are conditional factors for future generations, big marketing opportunities arise. This too could provide advantages in regard to certifications as LEED, which grants points for having recycled industrial content in the concrete [25].

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