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Use of e-plastic waste in concrete as a partial replacement of coarse mineral aggregate

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Abstract. The accelerated increase of the population growth rate in the world and the current lifestyle based on consumerism considerably increased the amount of waste generated by the human activity. Specifically, e-plastic waste causes significant damage to the environment because of its difficult degradation process. This paper aims to establish the feasibility of using e-plastic waste in concrete as a partial replacement of coarse mineral aggregate. Considering a control mix without e-plastic waste designed for a compressive strength of 21 MPa, tests on concrete mixes with 40, 50 and 60% of e-plastic waste aggregate to determine the fresh and hardened properties were carried out. A reduction in the compressive strength as the percentage of e-plastic waste increases was observed, the maximum reduction being 44% with respect to the control mix. In addition, a significant reduction as much as 22% in the density of the concrete mixes with e-plastic waste was recorded, which means that lighter elements can be produced with this type of concrete. Two new equations based on regression analysis of the experimental data from this study were proposed. These equations estimate the reduction in the compressive strength of concrete mixes with e-plastic waste aggregate at 14 and 28 days. A cost analysis and a practical alternative to introduce this waste material into the market are also presented.

Keywords: waste management; recycling; e-plastic waste; aggregates; compressive strength; social housing

1. Introduction

In modern times, the development of daily life has been framed by changes generated because of the accelerated progress of technology. Nowadays, the realization of almost any activity requires the use of electronic devices, either to store information, to use as a means of communication or simply for leisure. In the National Survey of Quality of Life, carried out in Colombia in 2015 (DANE 2016), 45.5% of the total households had a desktop computer, notebook, or tablet, while in 2012, the percentage of households with desktop or notebook computer was 38.4% within the total population. Factors such as population growth, the decline in the prices of technological articles, globalization and the growing need for households to incorporate technological tools that facilitate their day-to-day work have significantly increased the rate of acquisition of this type of items. Because of the progressive increase in the demand for electronic devices and the difficult process of degradation of the materials from which they are produced, in recent decades there have been problems with the treatment of this type of waste. According to the Ministry of Environment and Sustainable Development, annually between 20 and 50 million tons of e-waste are produced in the world. In Colombia, between 6000 and 9000 tons of computers, monitors and other similar components were discarded in 2007 (Ministerio de Ambiente 2014).

The waste materials that have been used as aggregates in the production of concrete mixes are the following: coal ash (Andrade *et al*. 2009, Kim and Lee 2011), ferrous and non-ferrous slag (Papayianni and Anastasiou 2010, Yüksel *et al*. 2011), waste from food and agricultural industries (Cyr and Ludmann 2006, Teo *et al*. 2010), pulp and paper mill waste (Ahmadi and Al-Khaja 2001, Naik *et al*. 2004), leather waste (Baffa and Akasaki 2005, Santiago *et al.* 2009), industrial sludge (Rao *et al*. 2009, Sales and de Souza 2009), mining industry waste (Kinuthia *et al*. 2009, Yellishetty *et al*. 2008), ceramic wastes (Guney *et al*. 2010, Pacheco-Torgal and Jalali 2010), plastic wastes (Akçaözoğlu *et al*. 2010, Asokan *et al*. 2010, Siddique *et al*. 2008), glass wastes (Wang *et al*. 2014, Wang and Chen 2008) and scrap tires (Bompa and Elghazouli 2017, Bompa *et al*. 2017, Elghazouli *et al*. 2018, Wang *et al*. 2012, Xu *et al*. 2018). Among the waste that can be found predominate two specific types, metals and polymers. In the particular case of metals, these are easily reusable because of their high commercial value. On the other hand, plastic type waste can take in degradation between 100 and 1000 years depending on its composition. Since 2010 Colombia has been working on the promulgation and consolidation of regulations that help mitigate the negative effect of e-plastic waste in our environment.

In previous investigations, the behaviour of plastic waste such as polyethylene terephthalate (PET) was generally studied because this material is commonly found in garbage dumps and waste conglomeration sites. In the study by Batayneh *et al*. (2007) the behaviour in compression, bending and indirect tension of different test

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specimens made from concrete with plastic waste of different types was studied. In that investigation, the authors concluded that the decrease in the resistance was generated almost linearly with respect to the plastic waste percentage incorporated. In the research by Jo *et al*. (2008) elements made from concrete with plastic waste were tested, this time the recycled material was used only from the processing of PET bottles. In that study, fine and coarse plastic waste aggregate were used separately, in order to carry out a more exhaustive test in which the effect of particle size distribution of the unconventional plastic waste aggregate added to the mix on the compressive strength was shown. Silva *et al*. (2013) determined the influence of the environmental conditions on the durability of the concrete containing selected plastic waste aggregate. Another study in which PET plastic materials was used is the one developed by Sadrmomtazi *et al*. (2016). In that research, a methodology similar to that used by Jo *et al*. (2008) in which the plastic waste material was used to replace the conventional fine aggregate was carried out. Additionally, superplasticizers were used in the mix design in order to improve the properties of the resulting fresh concrete and its final compressive strength.

A limited number of studies were reported on concrete with e-plastic waste. In the study conducted by Lakshmi and Nagan (2010) by laboratory tests on concrete mixes, the authors replaced conventional coarse aggregate with plastic from the grinding of e-plastic waste. They first made the characterization of the waste material and the coarse aggregate to be used, gradually determining the percentages of replaced coarse aggregate by e-plastic waste. The same authors one year later (Lakshmi and Nagan 2011) performed a series of tests on concrete mixes made from different e-plastic aggregate obtained from e-plastic waste, finding that the compressive strength decreases in a less pronounced way as the percentage of e-plastic waste added to the mixes increases. In the research by Senthil Kumar and Baskar (2015b) the compressive strength of concrete cubes with e-plastic waste was studied. It was observed the decrease of the compressive strength with the increase of e-plastic waste percentage. In the study carried out by Manatkar and Deshmukh (2015) it was observed that for concretes with compressive strengths equals to 20 MPa and 25 MPa with a replacement of up to 20% of coarse aggregate by e-plastic waste, there was a reduction in the compressive strength of concretes with e-plastic waste percentage greater than 10%. In the study by Akram, Sasidhar and Pasha (2015) it was observed that when e-plastic waste was used to replace coarse aggregate, there was a decrease in compressive strength, but when 10% of fly ash was also added results comparable to control mix were obtained. An experimental study on the utilization of e-plastic waste as fine aggregate was made by Gawatre and al. (2015). The effect on the compressive strength of 20 MPa concrete by utilizing 0, 20 and 30% of e-plastic waste was presented by Manjunath (2016). The addition of e-waste fibres to the concrete was studied by Kurup and Senthil Kumar (2017). It was found an increase in the compressive strength when 0.6 and 0.8% of e-waste fibres with respect to the weight of cement were used. The effects of e-plastic waste aggregate on water absorption and

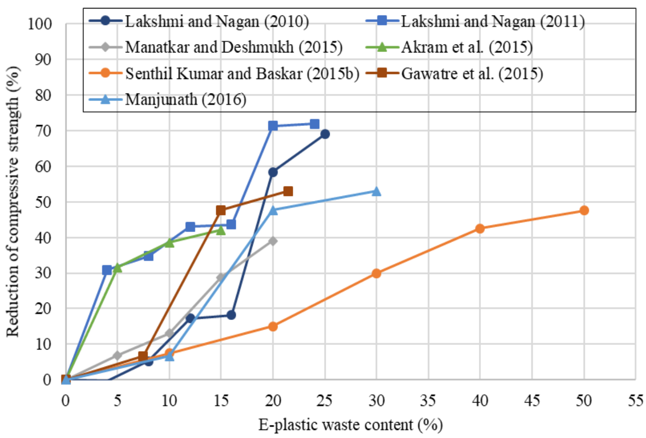

Fig. 1 Reduction of compressive strength vs. e-plastic waste content used in previous studies

sorptivity of concrete were presented by Senthil Kumar *et al*. (2017). The radioactivity of concrete made with e-plastic waste aggregate in terms of gamma radiation and radon emanation was presented in the study by Senthil Kumar *et al*. (2018).

Selected data from these previous studies is summarized in Fig. 1, which shows the reduction of the compressive strength as the percentage of e-plastic waste used in concrete mixes increases. The results from the study by Senthil Kumar and Baskar (2015b) show that as the compressive strength decreases, the decrease caused by the incorporation of the e-plastic waste aggregate becomes less and less significant. This could be due to the chemical composition and the proper shape of the e-plastic particles that varies significantly according to each waste selection and grinding process. For 20% of e-plastic waste content used in the mixes to replace mineral aggregate, it can be observed that the compressive strength of the concrete reported by Senthil Kumar and Baskar (2015b) decreases only 15%, a relatively low value compared to those reported by other studies. A contradictory result was reported by Arora and Dave (2013) where an increase in the compressive strength was found when 4% content of e-plastic waste was used.

The objective of this research was to design a concrete mix using plastic waste from the grinding of the housings of the electronic devices as coarse aggregate, the purpose being to deal with the sustainability issues of the e-plastic waste. The concrete thus obtained is to be used in non-structural elements as dividing walls in social housing in Barranquilla. The control mix without plastic waste was designed to meet the standards of quality in terms of compressive strength established by the Colombian Norm of Earthquake Resistant Construction, NSR-10 (Asociación Colombiana de Ingeniería Sísmica 2010) for structural concrete. In addition, the cost reduction that can be obtained when making this type of concrete with recycled aggregates with respect to the costs involved in the production of traditional concrete made from mineral aggregates is shown. Based on this experimental study Vargas and Polo (2017) realized their undergraduate thesis.

Fig. 2 E-plastic waste aggregate used in this study

Table 1 Mechanical properties of e-plastic waste

Property	Test method	ABS plastic
Tensile modulus (MPa)	ASTM D638 (2014)	2137
Tensile strength at yield (MPa)	ASTM D638 (2014)	42
Flexural modulus (MPa)	ASTM D790 (2015)	2344
Flexural strength at yield (MPa)	ASTM D790 (2015)	72
Rockwell hardness	ASTM D785 (2015)	R105
Notched izod impact at 23℃ (J/m)	ASTM D256 (2010)	415

Table 2 Physical properties of aggregates

Property	Fine aggregate	Coarse mineral aggregate	E-plastic waste aggregate
Unit weight (kg/m^3)	1620	1580	490
Specific gravity	2.65	2.55	0.93
Moisture content (%)	1.0	1.0	0.2
Absorption (%)	0.7	0.5	0.2
Fineness modulus	1.92	6.65	5.23

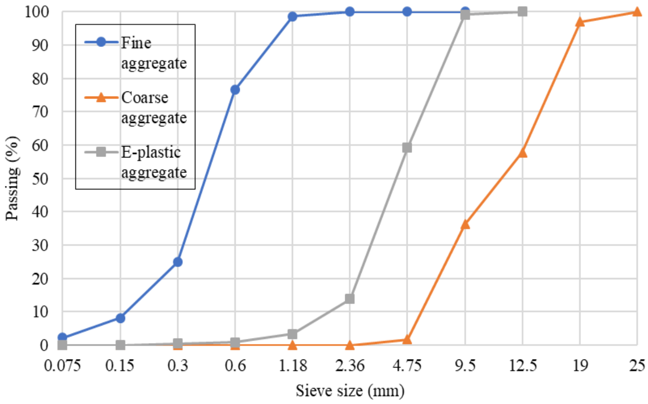

Fig. 3 Particle-size distribution of aggregates

2. Experimental programme

2.1 Materials

During the process of selecting the materials for the manufacture of concrete, materials traditionally used in the manufacture of in situ concrete in the Colombian Caribbean coast were selected, due to the search for a mix design whose materials were easy to acquire. The materials used for the realization of the mixes were the following: general use hydraulic cement from the cement company Argos (2017) according to ASTM C1157 (2011), fine aggregate as sand from the quarry of Santo Tomás from Atlántico department, coarse aggregate as gravel from the Ochoa quarry of Puerto Colombia from Atlántico department and e-plastic waste aggregate (Fig. 2).

The e-plastic waste aggregate was obtained from the grinding of computer housings. Acrylonitrile butadiene styrene, also called ABS is a compound commonly found in the manufacture of computer housings and other electronic devices because this thermoplastic material exhibits excellent mechanical behaviour and an exceptional ability to withstand chemical attacks (Plastics International 2017). All these properties were developed in order to provide strength and durability to materials made from this compound. The mechanical properties of the e-plastic waste used in this study that is made from the grinding of ABS plastic are taken from the literature (Plastics International 2017) and are presented in Table 1.

The particle size distribution of the aggregates as determined by a sieve analysis in accordance with ASTM C136 (2014) is presented in Fig. 3. The nominal maximum size of the coarse aggregate and e-plastic waste aggregate was 19 and 9.5 mm respectively.

The unit weight, specific gravity, moisture content, absorption and fineness modulus of fine, coarse and e-plastic waste aggregates were determined by experimental tests and are presented in Table 2. It is worth noting the low unit weight and specific gravity of the e-plastic waste aggregate.

2.2 Mix designs and specimen details

Four concrete mixes were made, a control one without e-plastic waste and another three with different percentages of ground e-plastic waste as 40, 50 and 60%. The addition of the e-plastic waste to the mix was done by replacing percentages of coarse mineral aggregate. Concrete mixes have been designed using ACI Committee 211 absolute volume method (ACI 211.1-91 1991). The parameters considered in the mix design were the following: compressive strength f'_c=21 MPa, minimum slump 25 mm, maximum slump 100 mm, nominal maximum size of aggregates 19 mm, water/cement ratio 0.53, air content 2%, unit weight of coarse aggregate 1580 kg/m^3, specific gravity of coarse aggregate 2.55, specific gravity of fine aggregate 2.65, specific gravity of cement 3.15. The maximum nominal size and unit weight of gravel and e-plastic waste, as well as the specific gravity of sand, gravel, e-plastic waste and cement, were determined by experimental tests. The mix proportions are summarized in Table 3.

The mixing was done by hand with a bricklayer's blunted trowel, without having a mixer. The mixing procedure was as follows: firstly, the cement and the fine aggregate were mixed, secondly the coarse mineral aggregate and the e-plastic waste aggregate were added to the mix and finally the water was added to the mix. In total,

Table 3 Mix proportions

E-plastic waste (%)	0	40	50	60
Water (kg/m^3)	198	198	198	198
Cement (kg/m^3)	373	373	373	373
Coarse aggregate (kg/m^3)	1053	368	283	201
Fine aggregate (kg/m^3)	639	639	639	639
E-plastic waste aggregate (kg/m^3)	0	248	279	308

Table 4 Fresh and hardened properties of concrete mixes

E-plastic waste (%)		0	40	50	60
Slump (mm)		62.5	75	75	100
Density (kg/m^3)	Mean	2426	2119	1991	1897
	SD	1.07	12.8	24.8	49.9
Compressive strength at 7 days (MPa)	Mean	13.2	11.8	8.93	8.78
	SD	0.02	1.84	0.50	0.20
Compressive strength at 14 days (MPa)	Mean	16.2	12.9	10.7	10.3
	SD	0.40	0.42	0.10	0.34
Compressive strength at 28 days (MPa)	Mean	18.8	14.8	12.4	10.5
	SD	0.21	0.78	1.16	0.08

Fig. 4 Slump test of e-plastic waste concrete

Fig. 5 E-plastic waste concrete cylinder piece after compression test

24 concrete cylinders of 150 by 300 mm have been moulded, 6 for each mix type, 2 for testing at 7 days, 2 for testing at 14 days and 2 for testing at 28 days. The consolidation of the moulded specimens was made by rodding and external vibration. To prevent the evaporation of water from the fresh concrete the specimens were covered immediately after finishing with a sheet of plastic. The specimens were demoulded after 2 days and stored in water storage tanks at a constant temperature of 23±2℃ until the time of testing according to ASTM C192 (2016).

3. Results and discussion

3.1 Properties of concrete mixes

The properties of the fresh concrete were determined immediately after the mixing procedure. The slump test was used to determine the consistency of the mixes according to ASTM C143 (2015). The density and compressive strength were determined according to ASTM C39 (2016) at 7, 14 and 28 days on 150 by 300 mm cylinders. A compression testing machine with a capacity of 2000 kN to determine the compressive strength of the specimens was used. A constant load rate of 0.25 MPa/s was applied by the testing machine during the test. The mean results of the fresh and hardened properties together with the standard deviation (SD) are presented in Table 4.

As can be seen in Table 4, the concrete mix without e-plastic waste reached at 7 days 70% of the compressive strength at 28 days, while the concrete with 60% of e-plastic waste reached at 7 days 84% of the compressive strength at 28 days. At 7 days the compressive strength of the concrete mix with 60% of e-plastic waste was 67% of the compressive strength of the concrete mix without e-plastic waste, meaning a 33% reduction in the compressive strength. At 28 days the compressive strength of the concrete mix with 60% of e-plastic waste was 56% of the compressive strength of the concrete mix without e-plastic waste, meaning a 44% reduction in the compressive strength. Based on the results obtained the concrete mix without e-plastic waste can be classified as normal weight concrete, with a density of 2426 kg/m^3. As expected for the concrete mixes with e-plastic waste lower densities have been recorded, the lowest value being recorded for the concrete mix with the highest percentage of e-plastic waste. The concrete mix with 60% of e-plastic waste showed a 22% decrease in the density with respect to the concrete mix without e-plastic waste, which means a 22% weight reduction. Concrete mixes with e-plastic waste also showed good behaviour in the fresh state, the slump test values registered with the Abrams cone were 75 and 100 mm (Fig. 4), which are the recommended values to be used for concrete walls (ACI 211.1-91 1991).

Concrete mixes without e-plastic waste reached at 28 days 91% of the design compressive strength, the 18.82 MPa average value being above the minimum required by the NSR-10 (Asociación Colombiana de Ingeniería Sísmica 2010) for structural concrete, which indicates a successful mix design. For concrete mixes with e-plastic waste, the 14.8, 12.4 and 10.5 MPa compressive strengths at 28 days can be considered satisfactory considering that this concrete will be used in non-structural elements as dividing walls. During the compression tests of concrete mixes with e-plastic waste it was observed an unusual failure mode of the cylinders, some of them splitting into pieces as can be seen in Fig. 5. This phenomenon can be attributed to the lack of

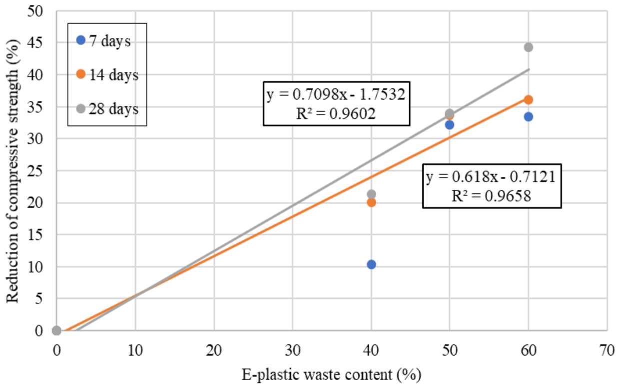

Fig. 6 Reduction of compressive strength vs. e-plastic waste content used in this study

adhesion between the cementitious matrix of concrete and the e-plastic waste aggregate used. Therefore, it is necessary to perform detailed studies to investigate this phenomenon and at the same time to obtain compressive strengths of at least 17 MPa to be able to use these concrete mixes with e-plastic waste in structural elements.

The variation of the compressive strength for the concrete mixes with e-plastic waste aggregate as a function of the e-plastic waste content is shown in Fig. 6. A reduction in the compressive strength as the percentage of e-plastic waste used in concrete mixes increases was observed. For the specimens cured 14 and 28 days, a linear relationship was used to estimate the trend of data in the form of Eqs. (1)-(2), where p_{ep} is the percentage of e-plastic waste aggregate and R_{pred} is the corresponding reduction in the compressive strength with regard to the control mix. For the specimens cured 7 days a clear trend of data was not observed.

$$R_{pred} = 0.62 \times p_{ep} - 0.71 \quad (1)$$

$$R_{pred} = 0.71 \times p_{ep} - 1.75 \quad (2)$$

The reduction in the compressive strength when e-plastic waste is used in the concrete mix can be estimated from Eq. (1) for specimens cured 14 days, and from Eq. (2) for specimens cured 28 days. The R-squared value for linear best fit was calculated as 0.96 for Eq. (1) and Eq. (2), which indicates very good correlation with the test results. These two equations and corresponding R-squared values (R^2) are also shown in Fig. 6.

3.2 Comparison of test results with other studies

The comparison of the test results with other studies reported in the literature is presented in Table 5 by the means of the ratio R_{test}/R_{pred}. R_{test} is the reduction in compressive strength obtained from tests and R_{pred} is the reduction in compressive strength by applying the Eq. (2) that was proposed based on the results obtained in this study. The water/cement ratio (*w/c*), the number of mixes with different content of e-plastic waste aggregate and the maximum percentage of e-plastic waste used $p_{ep\,max}$ are also shown in the Table 5 for each study. For this study, a very good agreement between the test results and the prediction of Eq. (2) was obtained with a ratio R_{test}/R_{pred} of 0.96. Considering the studies from the literature, a good agreement with the test results reported by Senthil Kumar and Baskar (2014, 2015a, 2015b) in the case of concrete mixes with 0.45 and 0.49 water/cement ratios was obtained. The ratio R_{test}/R_{pred} and the coefficient of variation (COV) obtained for the best agreement are 1.20 and 0.29 respectively. The other studies tend to overestimate the reduction in the compressive strength.

Table 5 Predictions of Eq. (2)

Author	*w/c*	No. mixes	$p_{ep\,max}$ (%)	R_{test}/R_{pred} (-) Mean	COV
This paper	0.53	3	60	0.96	0.15
Lakshmi and Nagan (2010)	0.55	6	25	2.42	0.78
Lakshmi and Nagan (2011)	0.55	6	24	9.77	0.95
Manatkar and Deshmukh (2015)	0.50	4	20	3.16	0.18
Akram *et al.* (2015)	0.50	3	15	9.85	0.69
Senthil Kumar and Baskar (2014)	0.45	3	50	1.20	0.29
	0.49	3	50	1.44	0.07
	0.53	3	50	2.87	0.46
Senthil Kumar and Baskar (2015a)	0.45	5	50	1.33	0.11
	0.53	5	50	2.61	0.39
Senthil Kumar and Baskar (2015b)	0.49	5	50	1.43	0.10
Gawatre *et al.* (2015)	0.45	3	21.5	3.71	0.48
Manjunath (2016)	0.50	3	30	2.59	0.50

The unit weight of the e-plastic waste material is a fundamental factor to be considered if comparisons are made with previous studies, because it is impossible to define standard characteristics for all types of e-plastic waste produced. The chemical composition and the form of grinding of these particles make unique each sample obtained from the recycling process.

3.3 Cost analysis

A practical alternative to introduce this material into the market could be to produce it in blocks that resemble the dimensions and shape of conventional concrete blocks used in the elaboration of masonry walls. In this way, the product would have no disadvantage in terms of the construction requirements with respect to masonry walls made from conventional materials such as the Samo clay block or conventional concrete block. The Samo clay block is a local material that was very used in the traditional masonry constructions. This block is made from clay and has the dimensions of (40x20x10) cm. The results obtained by comparing the material costs of 1 m^2 of masonry wall made from concrete blocks with e-plastic waste aggregate, Samo clay blocks and conventional concrete blocks are presented in Table 6.

The prices from the table are dimensionless and were calculated considering the price of the Samo clay block as reference, which was chosen one unit. From the results showed in Table 6 for the manufacture of 1 m^2 of masonry wall by means of the prototype of traditional construction

Table 6 Material quantities and costs for 1 m^2 of masonry wall

	Samo clay block	Conventional concrete block	E-plastic waste concrete block
Block dimensions (cm)	40×20×10	40×20×10	40×20×10
Block units	12.5	12.5	12.5
Portland cement (kg/m^2)	2.73	2.73	2.73
Fine aggregate (kg/m^2)	14.09	14.09	14.09
Block unit price (-)	1.00	1.55	1.17
Mortar price (-)	1.00	1.00	1.00
Total price (-)	2.00	2.55	2.17

by using Samo clay blocks and the one raised in this study by using e-plastic waste concrete blocks, it is possible to determine that the economic factor continues to prevail in the traditional construction. However, the difference in costs between using e-plastic waste concrete blocks and Samo clay blocks to manufacture 1 m^2 of masonry wall is only 8%. Also, by using plastic to replace mineral aggregates in concrete it is reduced the amount of waste generated by electronic devices which have a prolonged degradation stage. When comparing the costs involved by using concrete with e-plastic waste and conventional concrete it can be observed that it is more profitable to carry out the construction of the wall from concrete with e-plastic waste aggregate, the reduction in costs being 15%. The calculation of the costs involved in the manufacture of concrete with e-plastic waste aggregate does not include the costs associated with the acquisition of the recycled material, nor the costs generated as a result of its grinding and processing. The price of the materials was obtained through the application of a survey conducted in different quarries from Atlántico department in Colombia, so this price may vary according to the place where the activity is going to be carried out and the local conditions. The concrete with e-plastic waste aggregate in order to be economically feasible, the entity responsible for carrying out the project must have the necessary infrastructure for the collection, sorting and grinding of the e-plastic waste.

4. Conclusions

This research can lead to new uses of e-plastic waste materials, which means an improvement in the quality of the environment with respect to the treatment of composite materials such as ABS plastic. From the research carried out, it was possible to design a concrete mix with the use of ground e-plastic material, the waste of housings of electronic devices, replacing the traditional mineral aggregates. This concrete mix is to be used in the manufacture of concrete walls as dividing elements in social housing. The results from this study indicate the following:

- Most of the studies from the literature on concrete with e-plastic waste aggregate tend to overestimate the reduction in the compressive strength.
- All concrete mixes with e-plastic waste showed good workability in the fresh state, as indicated by the slump test values recorded.
- By replacing coarse mineral aggregate with e-plastic waste aggregate to make concrete a reduction in the compressive strength was recorded. The maximum reduction registered at 28 days that corresponds to 60% of e-plastic waste was 44%.
- A 22% weight reduction was recorded for the concrete mix with 60% of e-plastic waste with respect to the control mix without e-plastic waste.
- The lack of adhesion between the cementitious matrix of concrete and the e-plastic waste aggregate was noted in the compression tests. To address this problem, before the grinding process, once the material is controlled and classified, it must be processed according to the texture required to increase the bond strength with the cementitious material.
- The two equations proposed in this study Eqs. (1)-(2) show good correlation with the test results and can be used to estimate the reduction in the compressive strength of concrete mixes with e-plastic waste aggregate at 14 and 28 days.
- By using e-plastic waste to make concrete blocks a reduction in costs per m^2 of masonry wall as much as 15% can be obtained.

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