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Bibliographic Survey about the Use of Ceramic Waste as Recycled Aggregates in Concrete Production

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***Abstract*-** Civil construction industry is the responsible sector for a large amount of the world's economy, allowing job generation and directly interconnecting itself to the inputs, equipment and services production. During the execution of its most diverse activities, waste is generated in large quantities and, many of them end up being disposed improperly in the environment, causing several impacts on it. It is known that the majority of construction waste is made up of bricks, concrete and mortars. Therefore, the use of that waste can be an eco-efficient alternative to reduce environmental problems. Through a brief review, the aim of this article is to analyze and present the main pertinent technical knowledge regarding the incorporation of recycled ceramic materials (RCM) in concrete matrices. It was observed that a wide diversity of results can be obtained according to the nature of the ceramic waste, generation processes and treatment, grain-size distribution, among others. Some authors obtained an increase on abrasion resistance through the incorporation of those wastes. This property was superior even when compared to conventional concrete.

***Keywords*-** *Ceramic Waste, Recycled Aggregates, Concrete*

I. INTRODUCTION

As a direct consequence of the intrinsic activities to the construction industry, millions of tons of waste are generated each year. Global waste generation is estimated around 3 billion tons/year, which, if correctly managed, could lead to economic improvements and decreases in energy costs [1]. Only in Brazil, this number is around 70 million tons/year, may vary according to the human development index [2]. In addition, it is estimated that, about 50% to 75% of the raw materials extracted from nature returns in the form of waste within a period up to one year [3]. Also, [4] estimates that approximately 210 million tons of natural aggregates are consumed per year on construction industry. All this volume is mainly used for the production of mortars and concretes. Aggregates present a heterogeneous nature in general and about 40% to 85% of their composition consists on inert material, being the biggest source of them, concrete and ceramic materials [5].

Ceramic waste can be generated by ceramic industry, due to the losses of the finished product or by the construction and demolition activity, constituting a significant fraction of the generated waste. The amount of ceramic materials (bricks, tiles, sanitary ware, among others) present on construction and demolition waste (CDW) corresponds to 54% of the total and this fact illustrates the importance of the treatment and recovery of this type of residue [6].

According to [7], the CDW can be crushed for later incorporation in cementitious materials, being able to improve the mechanical properties and durability of these new materials. As a result, economic and environmental benefits could be achieved and part of the incorrect waste disposal would be solved. Regarding the use of ceramic materials waste in substitution of natural aggregates in cement matrixes, the results obtained by some authors, such as [8], show that the increment of the recycled aggregate percentages on alternative cements, results on a decrease of its density and increase of its water absorption. On the other hand, studies carried out by [9, 10], pointed to an 11% increase in compressive strength when a 25% content of recycled ceramic aggregates was introduced on the mixture. In addition, the authors [11, 12, 13] have concluded that the abrasion resistance of such concretes is generally higher than that of a concrete made with conventional aggregates.

Therefore, the main objective of this article consists in investigating and discerning about the technical knowledge pertinent to the different incorporation situations of the recycled ceramic residues in concrete matrices. With the accomplishment of this bibliographic survey, a higher conversance with the use of these residues as aggregates for eco-efficient concretes production is also aimed. Thus, more hypotheses can be elaborated, enriching the scientific community.

II. METODOLOGY

The starting point for overcoming most of the currently environmental problems will be the development of materials that can consume fewer inputs and, at the same time, emit fewer gases into the atmosphere. The challenge is, therefore, to build more, using fewer natural resources. So, it is important to establish practices that promote the use of waste, from different sectors, on new building materials production. This idea served as a premise for the development of the present study.

The research method used on this paper elaboration consists on a bibliographic review, with exploratory character, intending to obtain a higher familiarity with the use of ceramic material waste as aggregates in concretes, making possible the development of new hypotheses. Thus, through the study of national and international scientific documents, an analysis of the problem question was carried out.

III. State of Art: Researches with Ceramic Reclycled Aggregate in Concretes

In the following sections, the main properties observed in the recycled concrete, produced through the incorporation of ceramic waste in the cement matrix, will be discussed.

A. Ceramic Recycled Aggregate Properties

According to [14], aggregates are fundamental components for cementitious materials production. Its quality has a great influence on the elaboration of the desirable properties for a cementitious composite. However, the heterogeneity and contaminants presence in these materials are the main difficulties found to carry out their recycling [15]. Even in small quantities, the presence of contaminants, such as: glass, plastic, wood and soil particles, can directly interfere on the physical and mechanical properties of the produced aggregates, which, consequently, reduces the concretes compressive strength.

Tables I and II present characteristics found by some authors, concerning about the properties found in the recycled ceramic aggregates, both as fine and coarse aggregates.

Tables I and II allow to observe that, in general, the water absorption values of recycled ceramic aggregates are higher than those found on natural aggregates. A variation of this property of 10.7% (for fine aggregate) was verified, reaching up to 15.6% (for coarse aggregate). However, [16, 17] obtained different results from the others, with an absorption capacity of 0.2% and 0.6%, for the fine and coarse recycled aggregate, respectively, originated from sanitary ware. These low percentages may be due to the polishing of the primary material. According to [18], the high water absorption of the recycled aggregate originated from ceramic blocks occurs due to the high porosity of origin material of the aggregate. Probably, the high water absorption is the main limitation in the use of those aggregates in concrete production, without having losses in the mechanical strength, workability and durability of this material [11].

Another property of these recycled aggregates that tend to be elevated is the powdery material content (particles finer than 0.075 mm) reaching 22.1% (Table I) in the ceramic aggregate used in the studies of [22]. The quantity of those fines is related to the fragility of the waste that originated the recycled aggregate, as well as the adopted crushing process. In general, these smaller particles make the mixture require more water, given the greater specific surface area, directly influencing the workability of mixture. However, this powdery material may contribute to the reduction of the cementitious composite capillary absorption, as it tends to fill the pores of the cementitious matrix, preventing them from connecting, forming then the capillaries.

TABLE I. Main Properties of the Ceramic Waste as Fine aggregates

Authors	[8]	[13]	[16]	[19]	[20]	[21]
Ceramic Raw Material	Blocks	-	Sanitary Ware	Blocks and Tiles	Blocks	Blocks and Tiles
Crushing Process	Impact Crusher	Roller Mill	Jaw Crusher	Jaw Crusher and Roller Mill	-	Knife Crusher
Maximum Diameter (mm)	5.0	2.4	4.0	4.8	5.0	4.75
Fineness Modulus	-	2.08	-	2.50	-	2.15
Specific Gravity (g/cm³)	1.98	2.49	1.95 – 2.97	2.35	2.05	2.59
Water Absorption (%)	14.7	10.8	12.2 – 0.2	10.7	14.8	13.5
Particles < 75 µm (%)	-	22.1	-	-	-	-
Bulk Density (kg/dm³)	-	1.44	1.03 – 1.32	1.46	-	1.05

About the particle size distribution of the recycled aggregates, it is ideal to find a more continuous curve, which resembles to that one of the natural aggregates, thus benefiting the packing of the mixture. Concrete produced with fine recycled ceramic aggregates was studied by [8], and although their grains being coarser than the ones of the natural aggregates, the final combination generated a satisfactory particle size distribution curve for the concrete production through performing a partial replacement of the natural aggregate by the recycled one. This reduced the connectivity between the larger grains. Otherwise, it would tend to generate pores and intensify the water absorption of concrete by capillarity.

According to [18], the particle size distributions of the natural and recycled aggregates are comparable. However, the fine recycled aggregates, in general, are coarser than the natural ones.

TABLE II. MAIN PROPERTIES OF THE CERAMIC WASTE AS COARSE AGGREGATES

Authors	[11]	[17]	[18]	[19]	[23]
Ceramic Raw Material	Block	Sanitary Ware	Block	Blocks and Tiles	Tiles
Crushing Process	-	Jaw Crusher	-	Jaw Crusher and Roller Mill	Manual (hammer and sieve)
Maximum Diameter (mm)	9.5	12.5	-	19.0	20.0
Fineness Modulus	-	-	-	6.59	-
Specific Gravity (g/cm³)	2.03	2.39	2.50	1.86	2.22
Water Absorption (%)	12.0	0.6	11.5	15.6	14.4
Bulk Density (kg/m³)	1.16	-	1.92	1.26	-

B. Main Techniques Adopted for the Production of Recicled Concretes with Ceramic Waste

In order to correct some properties of the recycled ceramic aggregate and its possible negative effects on the concrete behavior, resulting from its incorporation, some techniques have been used in several studies. The pre-wetting process of those aggregates is one of them. It is used in order to correct the high water absorption that, according to [11], is the main problem of this aggregate. These authors adopted in their research, a simplified pre-wetting procedure of the coarse recycled ceramic aggregates, such manner it could be used in construction sites. This procedure consists of two steps:

- 30 first minutes: saturation period of the recycled aggregates;
- 30 minutes before mixing: drying period of the surface of the grains, when they are placed on plastic tarpaulin.

Similar procedure was adopted by [18], in their studies, also aiming to leave the recycled aggregates in the saturated surface dry condition and, thus, prevent them from absorbing water of the mixture. For this, the recycled aggregates were left immersed in water for a period of 24 hours. However, this procedure only succeeded with the use of the coarse recycled aggregates, since the fine fraction could not absorb 100% of the water at that time.

The pre-wetting of recycled aggregates also was performed by [19], in both fractions (coarse and fine). They were soaked 10 min before being put in the concrete mixer, with 80% of the absorbing water in 24 hours by the mass of the recycled aggregate. This process prevented part of the mixing water from being absorbed by the grains.

On the other hand, [8] chose to correct the workability loss, caused by the increase of the recycled fine ceramic aggregate content, through the use of a polycarboxylate based chemical admixture, thus maintaining the same workability in all produced concrete mixtures. This was also verified by [21], which on the same situation of workability loss, decided on making use of superplasticizers. This way, it was possible to achieve the workability needed for all samples, measured by the slump test.

C. Propeties of Recycled Concrete with Ceramic Waste

Table III presents the influence of the recycled ceramic residues on some properties found in the concretes with this addition, which will be discussed later.

1) Fresh State Properties:

In general, the replacement of the natural aggregate by the recycled ceramic aggregate, promotes significant changes in the concrete characteristics. Among them, it can be observed changes in their fresh state properties that correspond to the space of time in which the concrete remains plastic.

Table III shows that the variation on the replacement rates among the cited authors, are very close. Therefore, the w/c ratios were around the same amount for some authors. The increase of the recycled aggregate ceramic content makes the concrete require more water [18]. On the other hand, when the coarse recycled ceramic aggregate content increased, less water was needed. It was justified by the authors by the fact that the coarse fraction of the aggregate was completely internally saturated with water, while the fine fraction of them was not.

In general, it is observed that the concrete workability reduces with the increase of the replacement rate of the natural aggregates by the recycled ceramic ones, whether are they used in the fine or coarse fraction. This behavior was attributed by [24] to the greater roughness of the recycled aggregate surfaces, while [20] attributed this fact to the greater water absorption capacity of their grains. This increase in water absorption causes the reduction of the effective w/c ratio

In relation to the density of the concrete on fresh state, all the authors noticed a decrease of that property. According to [11] that behavior can be related to the lower specific gravity of the recycled aggregates used by these authors, when they are compared to natural aggregates.

2) Mechanical Behavior:

The data presented in Table III shows that the compressive and traction strength, obtained by the referred authors, increased in most of the cases, except the results obtained by [11, 18]. Such reduction in those mechanical properties, noticed in those two studies, may be related to the pre-wetting process applied for the recycled aggregates, which may generated an excess of water in the mixture, compromising the mechanical behavior of the concrete produced. On the other hand, the increase in the compressive and traction strength perceived in the other studies surveyed, may be related to the high water absorption of the recycled aggregates, which tends to reduce the effective water/cement ratio of the mixture, contributing thus to benefit such mechanical properties.

The performance of concretes with a replacement rate of 75% (natural aggregates by ceramic recycled aggregates) was analyzed by [22], and it was verified that the compressive

strength was little altered. However, they realized that, as the replacement rate increased, the tendency of those mixtures to present a slight reduction of that propriety was greater.

In relation to the flexural strength, although the angular shape and rough surface of the recycled aggregate are expected to benefit the bond between the grains and the cementitious paste, generating thus, increases in flexural strength [18], it was not what the authors noted. On the other hand, [9] observed a different behavior from concretes of the others authors. It was obtained an increase in both properties, compressive and flexural strength, when it was inserted in the mixture a replacement rate varying between 15% and 25%.

As for the modulus of elasticity, [18] obtained a reduction in that property, varying according to the replacement rate of the natural aggregate by the recycled one, originated from ceramic material. This reduction was 30%, 40% and 50% (when the fine, coarse, and both fraction of aggregate were used, respectively).

It is important to highlight, that in some studies, the mechanical behavior of the concrete produced proved to be favorable, as in the research [21]. In this work, it was studied the replacement by mass of the fine natural aggregate by the one originated by red ceramic waste (RCW) in concretes, at the rate of 20%, 40%, 60% and 80%, aiming to utilize that concrete in molded in-situ stakes. In order to evaluate its behavior under field conditions, three concrete stakes with 40% of RCW were made. The results showed that the strength and modulus of elasticity of the concrete increased as a function of the increase of the replacement rate. However, for values above 40% in this content of recycled aggregate, the concrete became unfeasible, once a large increase in the amount of admixture was necessary to maintain the desired workability. It was concluded that the addition of the RCW improved the physical and mechanical characteristics of the concrete, allowing its application in the stakes studied.

Abrasion resistance was another property that was improved in the studies [11, 12, 22], when incorporating the recycled aggregate originated of ceramic materials. According to [11], this favorable behavior is due to the better adhesion between the cementitious matrix and the recycled aggregate, given the higher porosity of the grains, when compared to those of the limestone aggregate. Bravo et al. [5] further supports that the main factor influencing the abrasion resistance is the aggregate size. When it is adopted the coarse recycled aggregate, this property tends to be improved, and worsened with the adoption of the fine recycled aggregate.

3) Durability Indicators:

According to [17], the durability indicators can be direct, which is when measuring the involved attack (chloride penetration and carbonation), or indirect, when measuring the transport parameters (water absorption, air and water permeability, porosity and electrical resistivity). The authors further state that both types are related by the porous structure of the concrete.

TABLE III. INFLUENCE OF THE CERAMIC WASTE ON THE PROPERTIES OF CONCRETES

Authors	[8]	[9]	[11]	[18]	[19]	[21]
ADOPTED METODOLOGY						
Fraction	Fine	Coarse	Fine and Coarse	Fine and Coarse	Fine and Coarse	Fine
Content (%)	10-50	15-25	100	25-100	25-100	20-80
W/C ratio	0.40	0.53-0.51	0.60	0.61-1.08	0.46-0.8	0.7-0.8
Admixture	Super-plasticizer (0.7-1%)	-	-	-	Super-plasticizer	Super-plasticizer (0.4%)
CHANGES IN THE CONCRETE PROPERTIES						
Slump (mm)	140-210	-	80 ± 10	60-70	120±20	170±20
Water Absorption (%)	↑ 51	-	-	↑ 12	-	-
Density (Fresh state) (%)	-	↓ 5.3	↓ 17	↓ 17	-	-
Air Entrained Content (%)	↑28	-	-	↑	↑ 15-64	↓ 9.3
Compr. Strength (%)	↑ 11	↑ 12	↓ 45	↓ 10-40	↓ 19-37 (coarse) ↑ 7-14 (fine)	↑ 25
Elasticity Modulus (%)	↑3.5	-	-	↓ 30-50	↓ 22-44 (coarse) ↓ 6-11 (fine)	↑ 34.8
Traction Strength (%)	↑ 8.6	↑ 24	↓ 26	↓ 15-40	-	↑

The concrete durability with incorporation of ceramic waste was evaluated by [25], and in the various mixtures produced, they concluded that even with the loss of compressive strength (when 20% of cement was replaced by that ceramic waste), the produced concretes presented an increase in the durability performance. That increase also was noticed in the concrete mixtures with replacement of the natural aggregate by the recycled ceramic one, comparing to the ordinary concrete.

In the studies of [26], which was used ceramic waste as coarse aggregate; the authors observed that although the mechanical behavior of that concrete was good, the durability performance was not. The authors pointed out the high water absorption (not only by immersion, but also by capillarity) of those materials, as the main reason of that bad performance, when the replacement rate increases in the concrete matrix.

Thus, possible aggressive agents can easily penetrate in the concrete, generating some problems to it, such as, carbonation and chloride attack. Therefore, it is necessary to adopt some techniques capable of easing that problem. Some authors [11, 26] observed that when the pre-wetting of the recycled aggregate (procedure commented in item *B*) was adopted, that problem could be partially solved. However, although that procedure can be easily performed in situ, the durability keep being one of the main problems noticed in the utilization of ceramic waste as recycled aggregate in concretes.

Analyzing the water absorption by capillarity of concretes, [18] observed, as expected, that concretes with recycled ceramic aggregates present a greater water absorption capacity than the conventional concretes. The replacement rate that presented the minimum values for this property were 75% for the recycled coarse aggregate and 25% for the recycled fine aggregate. They also observed that the use of admixtures as plasticizers had a beneficial effect on the recycled concrete produced, reducing water absorption capacity.

The increase of water absorption by capillarity in concrete with recycled ceramic aggregate was also observed in the research of [8]. However, the authors justify this behavior due to the greater presence of the fraction of grains of recycled aggregate in the mixture, greater than 4 mm (25%). They further stated that the larger the aggregate grain size, the greater the connectivity between them, thus increasing the water absorption by capillarity.

As regards the electrical resistivity, [17] noticed in their research that the increase of the replacement rate of recycled coarse aggregate (originated from ceramic sanitary ware) generated an increase of that property; it means that the concrete became fewer conductors. The increase observed in that property was from 17% to 31%, for the replacement rate of 20% and 25%, respectively. The authors relate that behavior to the isolation capacity of the recycled aggregate used by them, comparing to the natural coarse aggregate. No other researches evaluating that property were found in the bibliographic survey carried out to elaborate this paper.

Concerning the penetration of chloride ions, it was found by [17] that the entry of these ions into concrete with recycled ceramic sanitary ware aggregate was slightly higher than in the reference concretes (4% and 8%, for the replacement rate of 20% and 25%, respectively). That behavior was related to the greater total and capillary porosity of the recycled concrete. On the other hand, [8] worked with ceramic fine recycled aggregates, concluded that recycled concrete with this waste (up to 50% of substitution), presented similar or even higher resistance to penetration of chloride ions than the conventional concretes (during one year), once the penetration of chloride ions was reduced in these recycled concretes.

IV. CONCLUSIONS

After this study, it was noticed that, in general, the researches focused on the analysis of the influence of ceramic waste on concrete matrices, present a large range of results, ranging from a slight reduction in the mechanical properties up to an increase in the compressive strength, for example. This divergence can be explained due to the heterogeneity of the material. Waste is not produced by chance. It is originated because of the various productive processes of the construction industry. This way, its generation does not go through a quality control and its constituents can vary in content and characteristics. Therefore, different results can be obtained in researches where the same type of waste is studied.

With this bibliographic survey, it was also noticed, consensus between some authors in relation to the abrasion resistance of concretes produced with ceramic recycled aggregate in their composition. Generally, that property, when it is adopted that recycled coarse aggregate, is the one with the best results, showing superior performances even when compared with conventional concretes.

The recycled ceramic waste can present different characteristics, according to the place of production, the generation process, the percentages of compounds and contaminants, the particle size distribution, the nature of the ceramic material, the residue phase, regional and climatic factors, packing of particles, among others.

With the accomplishment of this bibliographic survey, it was realized that the more studies are developed regarding the use of the ceramic waste in its most diverse applications, the better it will be for the scientific community. There is the hope that this research can contribute to the improvement of the knowledge related to the use of this material.

Finally, the results obtained with this research showed that further studies and investigations should be developed in order to understand and determine better procedures for correction/mitigation of some properties of the ceramic waste as recycled aggregate. Among them, emphasis can be placed on the porosity and water absorption of that aggregate. With the information presented in this paper, it is clear that the higher water absorption rate of the aggregate, due to its higher porosity, were mainly responsible for the negative effect on some properties of the concretes produced with this type of aggregate, especially for requiring more water in the mixture. Moreover, it is interesting to study these residues in their least heterogeneous form possible. Thus, contaminants and finer particles will not interfere so much in the characteristics of that material.

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