CONCRETE WASTE AS COARSE AGGREGATE IN CEMENTITIOUS MATRICES: REVIEW

RESÍDUOS DE CONCRETO COMO AGREGADO GRAÚDO EM MATRIZES CIMENTÍCIAS: REVISÃO

RESIDUOS DE HORMIGÓN COMO ÁRIDO GRUESO EN MATRICES CEMENTANTES:REVISIÓN

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ABSTRACT

The aggregates present in concrete composition are non-renewable resources obtained through multiple mining or extraction innovations, which cause significant damage to nature. At the same time, the increasing generation of concrete waste is a worrisome reality. Most construction and demolition waste is quimically inert and non-hazardous, however it represents a problem when it is disposed of, since landfills have their useful life shortened due to the large volume of this type of disposal. Therefore, this article's objective is to survey the caracteristics of concrete waste and the properties of concretes produced using this type of residue as coarse aggregate. A systematic literature review is carried out and the feasibility of applying hardened concrete waste as recycled aggregate in cement matrices is discussed. It is observed that composites with recycled aggregates present similar characteristics to conventional concrete, being within usable ranges based on normative references, such as the properties of compressive strength, water absorption, density and modulus of elasticity. Therefore, it is viable to incorporate recycled aggregates as partial replacement for conventional aggregates.

KEYWORDS

Recycled concrete; Concrete waste; Coarse aggregate; Cementitious matrices.

RESUMO

Os agregados presentes na composição do concreto são recursos não renováveis obtidos através de múltiplas inovações de mineração ou extração, que causam danos significativos à natureza. Ao mesmo tempo, a crescente geração de resíduos de concreto é uma realidade preocupante. A maioria dos resíduos de construção e demolição é quimicamente inerte e não perigosa; no entanto, representa um problema quando é descartada, pois os aterros sanitários têm sua vida útil reduzida devido ao grande volume desse tipo de descarte. Portanto, o objetivo deste artigo é analisar as características dos resíduos de concreto e as propriedades dos concretos produzidos utilizando esse tipo de resíduo como agregado graúdo. Realiza-se uma revisão sistemática da literatura e discute-se a viabilidade de aplicar resíduos de concreto endurecido como agregado reciclado em matrizes cimentícias. Observa-se que os compósitos com agregados reciclados apresentam características semelhantes ao concreto convencional, estando dentro de faixas utilizáveis com base em referências normativas, como as propriedades de resistência à compressão, absorção de água, densidade e módulo de elasticidade. Portanto, é viável incorporar agregados reciclados como substituição parcial dos agregados convencionais.

PALAVRAS-CHAVE

Concreto reciclado, resíduos de concreto, agregado graúdo e matrizes cimentícias.

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RESUMEN

Los agregados presentes en la composición del hormigón son recursos no renovables obtenidos a través de múltiples innovaciones de minería o extracción, que causan daños significativos a la naturaleza. Al mismo tiempo, la creciente generación de residuos de hormigón es una realidad preocupante. La mayoría de los residuos de construcción y demolición son químicamente inertes y no peligrosos; sin embargo, representan un problema cuando se disponen, ya que los vertederos ven acortada su vida útil debido al gran volumen de este tipo de desechos. Por lo tanto, el objetivo de este artículo es analizar las características de los residuos de hormigón y las propiedades de los hormigones producidos utilizando este tipo de residuo como árido grueso. Se realiza una revisión sistemática de la literatura y se discute la viabilidad de aplicar residuos de hormigón endurecido como agregado reciclado en matrices cementantes. Se observa que los compuestos con agregados reciclados presentan características similares al hormigón convencional, estando dentro de los rangos utilizables según las referencias normativas, como las propiedades de resistencia a la compresión, absorción de agua, densidad y módulo de elasticidad. Por lo tanto, es viable incorporar agregados reciclados como reemplazo parcial de los agregados convencionales.

PALABRAS CLAVE

Hormigón reciclado, residuos de hormigón, árido grueso, matrices cementantes.

1. INTRODUCTION

Concrete is one of the most used materials in the world. The aggregates most commonly presente in its composition, namely sand and crushed stone, are non-renewable resources obtained through multiple stages of mining or extration.

To satisfy the growing global demand for these aggregates, 50 billion tons of natural river sand and gravel are extracted every year (CHANDRU; BAHURUDEEN; SENTHILKUMAR, 2023). Recent research points to a possible shortage of these materials if the same extraction rate continues to be followed (MAKUL *et al.*, 2021; ESTOKOVÁ; FABIÁNOVÁ; ONDOVÁ, 2022). In Brazil, the demand for natural aggregates in 2023 was 654 million tons, of which 272 million tons were crushed stone (ANEPAC, 2024). According to Araújo (2011), the production of crushed stone causes catastrophic effects on the environment, such as air and water pollution, noise and visual pollution, in addition to the accumulation of solid waste.

Allied to the utilization of concrete, there is the production of ever-increasing amounts of construction and demolition waste. The inadequate management of this waste can cause serious environmental problems (ZHANG *et al.*, 2023). Worldwide, construction and demolition activities contribute to the production of ten billion tons of waste each year and this production is constantly growing (KABIRIFAR *et al.*, 2021; WANG *et al.*, 2019). Most construction and demolition waste is inert and non-hazardous, but may contain substances harmful to the environment such as asbestos, organic pollutants and heavy metal (TRIVEDI *et al.*, 2023).

Due to the leaching of heavy metals, these residues become prone to soil and water pollution (ZHENG *et al.*, 2017). Furthermore, the civil construction waste represents a disposal problem, due to which sanitary landfills have their useful life shortened, due to the large volume of landfilled waste or the inadequate occupation of useful land that is converted into waste disposal (DEVI *et al.*, 2023).

Among the various types of construction and demolition waste, hardened concrete is presente in large quantities. However, concrete waste, particularly that from demolition, is a highly heterogeneous material and tends to absorb large amounts of water. The aggregates present in the concrete are also difficult to use, as the hydrated cement that surrounds the surface of the aggregates compromises the adhesion of the new mixture constituents (NEDELJKOVI *et al.*, 2021). Instability under compression forces (TANTA *et al.*, 2022) limits the use of recycled concrete in the manufacture of new concrete for structural use (TRAN; DANG; HO, 2022). On the other hand, recent studies point to the feasibility of using recycled concrete, reducing the environmental impact caused by construction waste (BALDANIA; BHOGAYATA, 2023).

With a focus on sustainable development, the search for other sources of concrete aggregates is crucial and the recycling of concrete waste presents itself as a promising alternative. Reusing this waste means reducing the need to extract new materials, which could represent a reduction in the consumption of natural aggregates by 60% (BRAVO *et al.*, 2015).

Furthermore, when compared to natural aggregates, recycled aggregates emit 28% less carbon dioxide due to the lower energy incorporated in their production and transportation process (TAM *et al.*, 2018). Thus, the incorporation of construction and demolition waste to replace natural aggregates represents the promotion of more sustainable and responsible development, as it contributes to reducing the ecological footprint caused by the construction sector.

For this paper, a bibliographical review was carried out, with the selection of studies that addressed the feasibility of applying waste composed of hardened concrete, as coarse aggregate in the production of recycled concrete. By tabulating the collected data, the main properties of the resulting concretes were analysed and discussed.

2. METHODOLOGY

For the paper production, a bibliographic research methodology was employed. The "Periódicos Capes", "Google Scholar", "Scopus", "Science Direct" and "Web of Science" databases were used, in addition to academic institutional repositories. The terms "concrete", "hardened", "crushed", "waste", "construction", "reuse", "recycled", "eco-friendly" were used as keywords for the research, limiting the selection to those studies published in the past ten years.

In order to refine the searches, the boolean logical operators "AND", "OR" and "NOT" were used, with the aim of combining search terms or expressions, as well as a proximity operator (double quotes) to search for compound terms, since this operator determines the maximum distance between terms or expressions in a document, making the search more objective. Twenty articles about the use of recycled concrete aggregate as substitute for conventional aggregate in concretes were selected.

Although the waste was classified as "hardened concrete waste" by the selected authors, it is important to highlight that according to NBR 9935, recycled concrete aggregates (RCA) are those obtained through the recycling of concrete in a fresh or hardened state, whose coarse fraction (> 4.75 mm) is made up of at least 90% of fragments composed of Portland cement, by mass. Mixed recycled aggregates (MRA) are those whose coarse fraction (> 4.75 mm) consists of a maximum of 90% of fragments composed of Portland cement, by mass (ABNT, 2011).

Among the selected studies, 15 publications refer to normal concrete, 2 to pavement materials, 2 to structural concrete and 1 to self-compacting concrete. In all cases, natural coarse aggregates was replaced through the manufacture of recycled coarse aggregates from concrete waste.

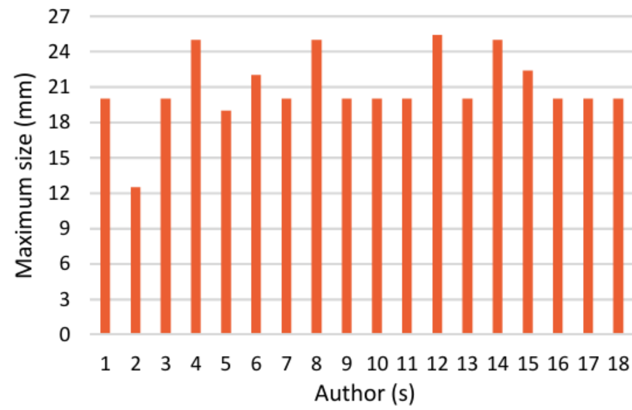
Once the research and selection of the various sources of information were carried out, the collected data was tabulated and subsequently presented in the form of graphs for data analysis. Consequently, discussions and conclusive comments were made.

3. RESULTS AND DISCUSSION

The results and discussions regarding the physical properties of the recycled aggregates are presented, namely: maximum size, density and water absorption rate. Durability and mechanical resistance indexes of the concretes produced with these aggregates are also presented, namely: water absorption rate, compressive strength, flexural tensile strength, diametrical compression tensile strength and modulus of elasticity.

3.1. Concrete waste

Figure 01 shows the maximum size of the recycled coarse aggregate used by different authors in the production of concrete. There is a The results for the water absorption rate of recycled aggregates (Figure 03) showed great variability between the selected studies, with the minimum, maximum and average values equal to 2.76% (SURYA, *et al,* 2013), 7.35% (GHORBEL; WARDEH, 2017) and 4.21% respectively.

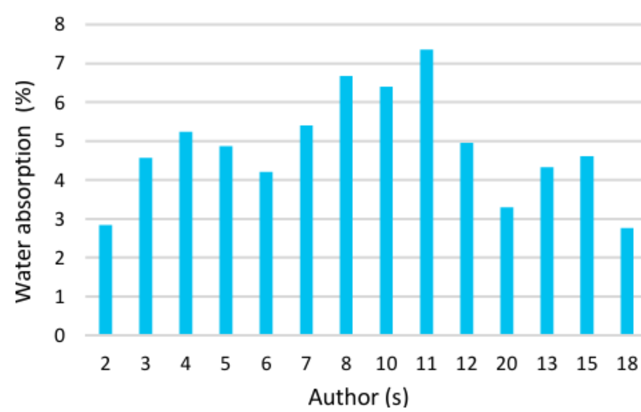


1 - Harish; Ramana; Gnaneswar, 2021; 2 - Xiong *et al,* 2021; 3 - Poongodi *et al,* 2021; 4 - Barhmaiah; Priyanka; Padmakar, 2020; 5 - Mohammed Ali; Zidan; Ahmed, 2020; 6 - Pacheco *et al,* 2019; 7 - Adessina *et al,* 2019; 8 - Ghorbani *et al,* 2019; 9 - Wang *et al,* 2019; 10 - Thomas; Thaickavil; Wilson, 2018; 11 - Ghorbel; Wardeh, 2017; 12 - Hamad; Dawi, 2017; 13 - Gupta; Khaudhair; Ahuja, 2016; 14 - Abdel-Hay, 2015; 15 - Soares *et al,* 2014; 16 - Orie; Orojo, 2014; 17 - Vyas; Patel; Bhatt, 2013; 18 - Surya; Kanta; Lakshmy, 2013.

Figure 01: Recycled aggregate's maximum size

Source: Authors (2023).

The high water absorption rate (Figure 2) presented by this type of aggregate is well above the limit values defined by NBR 15844 (ABNT, 2015) and C615 (ASTM, 2023) for granitic rocks (<0.4%) and by ASTM-C568 (ASTM, 2022) for high-density limestone rocks (≤ 0.3%). In regard to the size of the aggregates, there is a variation from 12.5 mm to 25 mm, with the maximum size of 20 mm being the most used among the authors of the selected studies. This results are within the dimensional range (4.75 mm to 75 mm) defined by NBR 7211 (ABNT, 2022) for coarse aggregates.

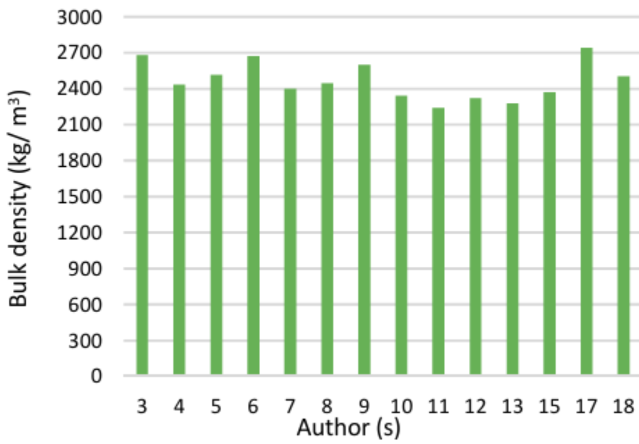


2 - Xiong *et al,* 2021; 3 - Poongodi *et al,* 2021; 4 - Barhmaiah; Priyanka; Padmakar, 2020; 5 - Mohammed Ali; Zidan; Ahmed, 2020; 6 - Pacheco *et al,* 2019; 7 - Adessina *et al,* 2019; 8 - Ghorbani *et al,* 2019; 10 - Thomas; Thaickavil; Wilson, 2018; 11 - Ghorbel; Wardeh, 2017; 12 - Hamad; Dawi, 2017; 13 - Gupta; Khaudhair; Ahuja, 2016; 15 - Soares *et al,* 2014; 18 - Surya; Kanta; Lakshmy, 2013; 20 - Fraile-Garcia *et al,* 2017.

Figure 02: Recycled aggregate's water absorption ratio

Source: Authors (2023).

The bulk density (Figure 3) of the recycled coarse aggregate ranged from 2,240 kg/m³ (GHORBEL; WARDEH, 2017) to 2,740 kg/m³(VYAS *et al,* 2013). Among the results, the average density was 2,501 kg/m. For purposes of comparing the nature of the material, the reference given by NBR 15844 (ABNT, 2015) establishes that the density for granitic rocks must be greater than 2,550 kg/m^3. By C568 (ASTM, 2022), the density must be greater than 2,560 kg/m^3 for high density limestone rocks. This range is close to the values found for the density of the recycled aggregate (Figure 02).



3 - Poongodi *et al,* 2021; 4 - Barhmaiah; Priyanka; Padmakar, 2020; 5 - Mohammed Ali; Zidan; Ahmed, 2020; 6 - Pacheco *et al,* 2019; 7 - Adessina *et al,* 2019; 8 - Ghorbani *et al,* 2019; 9 - Wang *et al,* 2019; 10 - Thomas; Thaickavil; Wilson, 2018; 11 - Ghorbel; Wardeh, 2017; 12 - Hamad; Dawi, 2017; 13 - Gupta; Khaudhair; Ahuja, 2016; 15 - Soares *et al,* 2014; 17 - Vyas; Patel; Bhatt, 2013; 18 - Surya; Kanta; Lakshmy, 2013.

Figure 03: Recycled aggregate's bulk density

Source: Authors (2023).

3.2. Physical properties

For the dosage of concrete mixtures, the water/cement ratio was kept constant in the majority of studies (Figure 04). Among the authors, the rate varied from 0.26 (MOHAMMED ALI, *et al,* 2020) to 0.61 (POONGODI *et al,* 2021). It is noteworthy that, according to the authors, to reach the value of 0.26, a superplasticizing additive was used, at a constant rate of 2% in all mixtures tested.

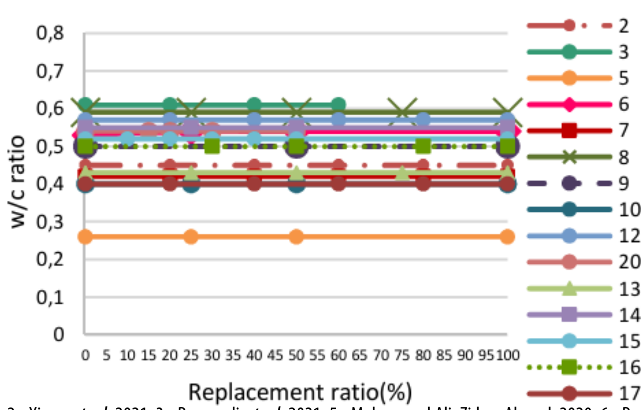


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Figure 04: Recycled aggregate's bulk density

Source: Authors (2023).

In GHORBEL & WARDEH (2017) however, cement consumption varied depending on the replacement ratio of natural coarse aggregate by recycled coarse aggregate. According to the authors, in order for the w/c ratio to be kept constant, it was necessary to vary the quantities of cement, since the high rate of water absorption by the recycled aggregate created the need for additional water to be incorporated into the mixtures.

The amount of cement used in the studies varied from 294 kg/m^3 to 479 kg/m^3, with the average value (384 kg/m^3) being higher than the minimum cement consumption determined by NBR 12655 (ABNT, 2022), for concrete subjected to Class I aggressiveness (260 kg/m^3).

It is observed an increase in water demand as the proportion of recycled aggregate increases. Nevertheless, the values for the w/c ratio, presented by different authors, were lower than the maximum value determined by NBR 12655 (ABNT, 2022) for concrete in Class I aggressive environments (≤0.65). In four studies, the value of the w/c ratio was below the maximum normative value for concrete in aggressive Class IV environments (≤0.45).

Figure 05 shows the rate of variation in slump for concretes produced with recycled aggregates and those produced with natural aggregates. Among the eleven studies in which this property was presented, the highlight is the decrease of up to 57% in the slump values obtained by Abdel-Hay (2015), in which no superplasticizing additive was used in the mixtures.

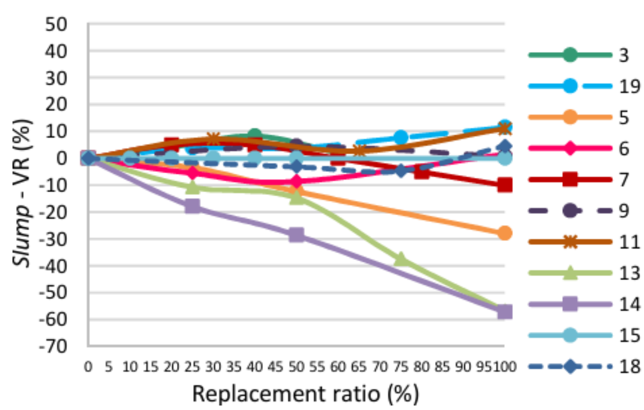

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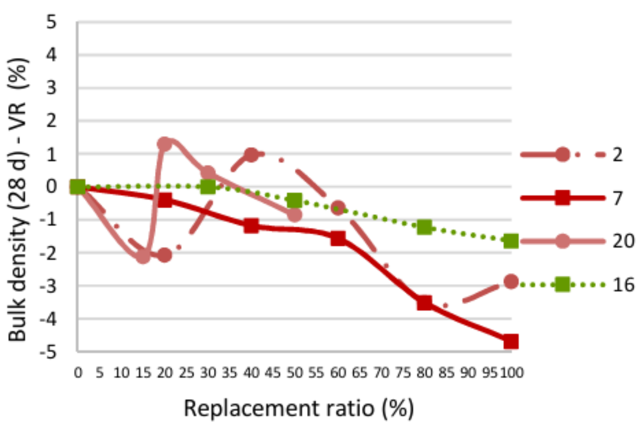
Figure 05: Variation in the slump flow values among mixtures.

Source: Authors (2023).

In Gupta *et al.* (2016), the superplasticizer additive content was kept constant for all concrete mixtures, which according to the authors explains the progressive drop in slump test values. This fact is related to the increase in the replacement content of aggregates, which leads to an increase in the amount of old, more porous mortar, adhered to the recycled aggregate. This results in a decrease of free water and, consequently, of the workability of the mortar mixtures. The variations occur because there is a greater wetting area in the aggregates, which require more water than conventional ones, impacting the workability and plasticity acquired by the mixture.

The rates of variation in the bulk density of concretes produced with different proportions of recycled coarse aggregate, after 28 days, are shown in Figure 06.



2 - Xiong *et al,* 2021; 7 - Adessina *et al,* 2019; 8 - Ghorbani *et al,* 2019; 16 - Orie; Orojo, 2014; 20 - Fraile-Garcia *et al,* 2017.

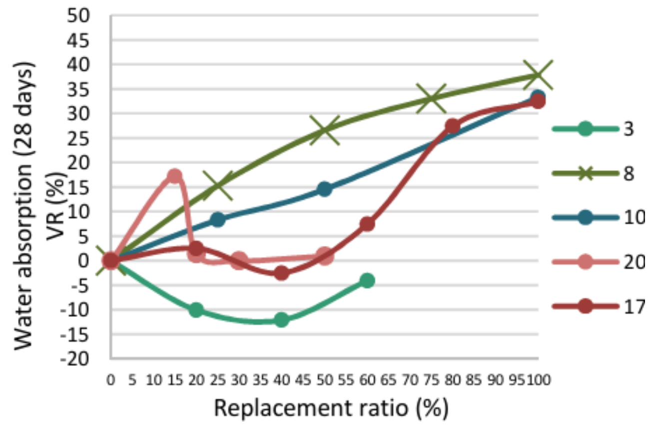
Figure 06: Variation in the slump flow values among mixtures.

Source: Authors (2023).

In general, a slight drop in density values is observed according to the replacement ratio of aggregates. In this context, an optimal substitution level is observed, with variations of ± 2.0%, around 20% substitution. This fact is related to the porous mortar adhered to the recycled aggregate which influence the connection between the constituents by increasing the porosity in the aggregate-paste transition zone. The concretes produced with total replacement of natural coarse aggregates showed the highest rates of decrease in density values (up to 5%), in relation to the reference concretes.

3.3. Durability and mechanical properties

Figure 07 shows the rates of change in water absorption of concretes produced with recycled aggregates, after 28 days, compared to conventional concretes.



3 - Poongodi *et al,* 2021; 8 - Ghorbani *et al,* 2019; 10 - Thomas; Thaickavil; Wilson, 2018; 17 - Vyas; Patel; Bhatt, 2013; 20 - Fraile-Garcia *et al,* 2017.

Figure 07: Variation in the water absorption ratio among mixtures

Source: Authors (2023).

There is a tendency for water absorption to increase (up to 38%) with the total replacement of coarse aggregates. The results presented by Poongodi *et al.* (2021) are an exception. According to the authors, the drop in water absorption is due to the filler effect caused by the addition of fly ash to the mixtures, as well as the pozzolanic reactions facilitated by the addition of silica fume, both capable of promoting the densification of cement matrices and, consequently, a decrease in water absorption rates. However, in general, increasing the replacement content of aggregates leads to greater water absorption.

It is noteworthy that, in four studies, water absorption values are below the maximum value (≤10%) determined by NBR 6136 (ABNT, 2016) for Class B or C concrete, with or without structural function, produced with natural aggregates.

It is observed that this is a property directly related to the physical properties that lead to durability indicators, since it is possible to evaluate the behavior trends of concrete with the addition of recycled aggregates against water, a potentially aggressive agent.

After 28 days, the porosity of the concretes with recycled aggregates increased by 28%, 44% and 52% for coarse aggregate replacement levels equal to 30%, 65% and 100%, respectively (GHORBEL; WARDEH, 2017). Similarly, the sorptivity of the recycled concretes, resulted in increases of 193%, 286% and 406% for replacement levels equal to 60%, 80% and 100% (VYAS *et al.*, 2013).

The compressive strength of concretes at 28 days are shown in Figure 08. Despite the great variability among the results, a downward trend in resistance values can be seen from low levels of replacement (10%) of natural coarse aggregates with recycled aggregate.

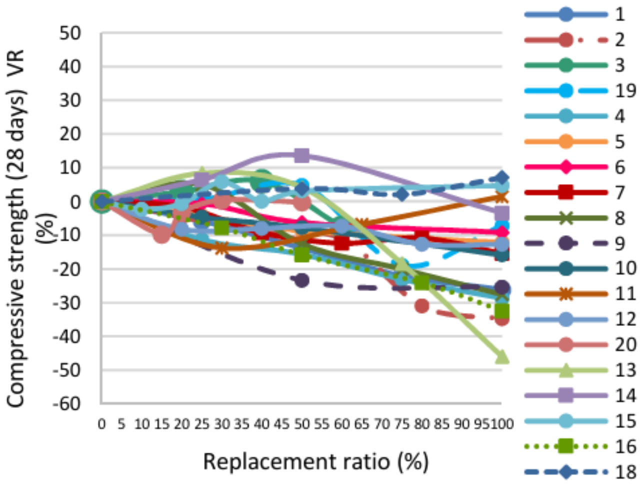


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Figure 08: Variation in compressive strength among mixtures

Source: Authors (2023).

For 100% replacement content, Gupta *et al.* (2016) resulted in a decrease in compressive strength of up to 46%. According to the authors, it is important to highlight that, in a normal dosage, when replacing aggregates, the masses of recycled and natural coarse aggregates are considered equivalent. For this purpose, the old mortar adhered to the recycled aggregate is considered an integral part of it. However, it is known that the strength of the adhered mortar is lower than the strength of the aggregate which, in part, could explain the drop in the strength values obtained in the tests. Furthermore, there is an increase in the transition zone between aggregates and mortar residues, which are identified as areas of great fragility. For this work, a constant water/cement factor was used, in addition to a superplasticizing additive, also at a constant fraction. Even so, in all studies, recycled concrete exhibited compressive strength greater than the minimum value (20 MPa) determined by NBR 8953 (ABNT, 2015).

The rates of variation in flexural strength are, shown in Figure 09, which analyzes the evolution of this property depending on the reference. In all studies presented, the flexural strength, tested at 28 days, also decreased after replacing 50% of natural coarse aggregate by recycled aggregate. The biggest drop (32%) was shown by concrete produced with total replacement of natural coarse aggregate (ORIE, OROJO, 2014).

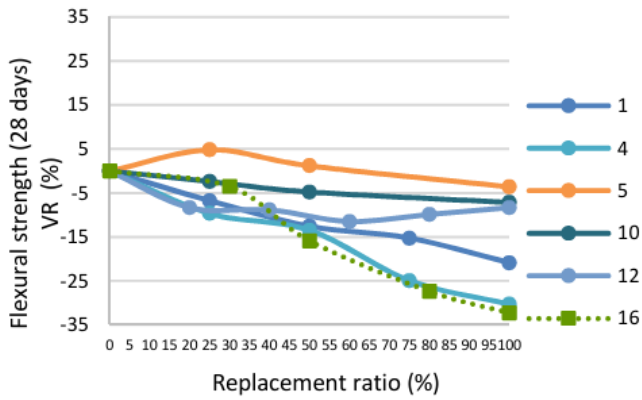

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Figure 09: Variation in flexural strength among mixtures

Source: Authors (2023).

This fact may be related to changes in the packaging of the mixture particles and changes in water absorption generated by recycled aggregates, in addition to areas of weakness at the interface between aggregates and old mortars, as well as with the final mortars molded in the study.

The rates of variation in tensile strength, obtained through the diametrical compression test, also showed a downward trend in ten of the twelve studies presented in Figure 10. For the majority of these studies, the largest drops (33%) correspond to the concretes produced with complete replacement of natural coarse aggregate with recycled ones.

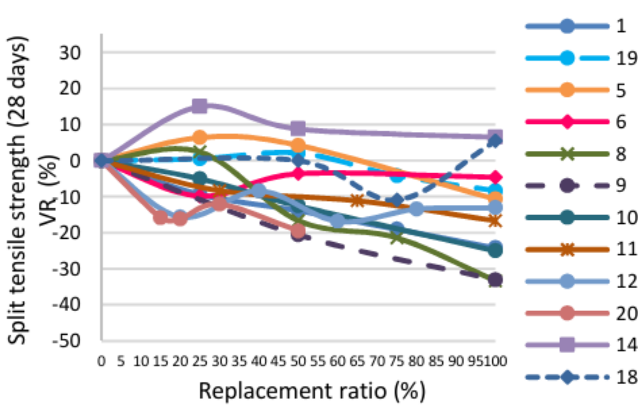

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Figure 10: Variation in the split tensile strenght among mixtures

Source: Authors (2023).

According to Surya *et al.* (2013), whose results showed an increase in tensile strength for the content of 100% replacement of natural coarse aggregate, the rough texture of the recycled aggregate and the absorption capacity of the mortar adhered to it, may have provided better adhesion and interlocking between mortar and recycled coarse aggregate, improving tensile strength.

Tested in eight studies, the modulus of elasticity (Figure 11) also showed a drop at the lowest levels of replacement of natural aggregate with recycled aggregate (20%).

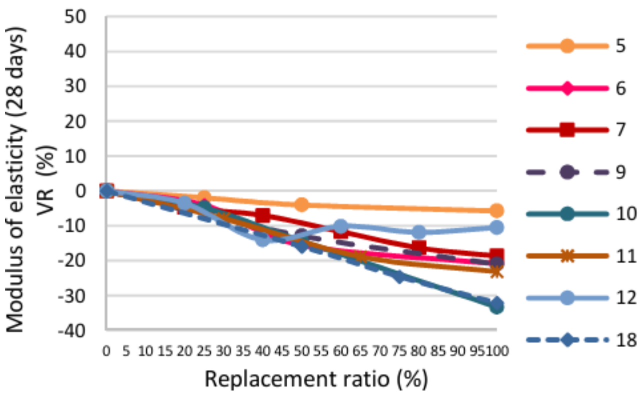

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Figure 11: Variation in the modulus of elasticity among mixtures

Source: Authors (2023).

It is observed that the biggest drops (32% and 33%), related to the complete replacement of coarse aggregate, were recorded by Surya *et al.* (2013) and by Thomas *et al.* (2018), respectively

This characteristic can be explained by the lower modulus of elasticity of recycled aggregates, which leads to greater deformation of mixtures with recycled aggregates (SURYA *et al.*, 2013).

4. FINAL CONSIDERATIONS

The literature review carried out for this article included studies on the application of hardened concrete waste as a substitute for natural coarse aggregate in concrete production. The tabulation of the collected data allowed the analysis of the main properties of the recycled aggregates, as well as the resulting concretes.

The maximum size and apparent density of recycled aggregates are similar to those of natural coarse aggregates. However, the high water absorption rate of this type of aggregate, up to 7.35% higher than natural coarse aggregates, is a limiting factor for its application in concrete production. Therefore, a more careful dosage is necessary in order to correct the amount of water added to the mixture, while paying attention to the limit values of the water/cement ratio.

In general, the values referring to the durability parameters (water absorption, porosity and sorptivity) of recycled concretes showed a drop when compared to those exhibited by reference concretes, produced without replacing natural aggregates. However, among the studies in which the water absorption rate was tested, the majority showed results below the maximum normative value (10%) for concrete blocks with or without structural function, indicating a possible use for this type of concrete.

Likewise, the mechanical strength of recycled concretes also decreased compared to reference concretes, but still, in all selected studies, recycled concretes exhibited compressive strength values higher than the minimum normative value (20 MPa), which also points to the technical feasibility of using recycled concrete.

It is observed that changes in the properties of concretes and mortars using recycled aggregates are related to the lower density of the materials and the greater absorption of water, resulting from the surface of the aggregates, which may contain adhered old mortar. In this sense, the application of this material brings about a tendency for changes in plasticity, water absorption and, finally, particle packaging, taking into account the material's resistance.

Since the incorporation of concrete waste as a substitute for natural coarse aggregates appears, in principle, to be a viable alternative for reducing environmental liabilities caused by civil construction, the gap that still exists in the literature regarding the properties of this type of recycled aggregate is highlighted and the appreciable potential for it's use indicates a real possibility of a more responsible, clean and sustainable development.

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RDB: methodology, visualization, writing - original draft and writing - review & editing.

WJS: conceptualization, formal analysis, methodology, project administration, supervision, writing - original draft and writing - review & editing.

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