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Environment

Incorporation of rubber ash as a partial substitute of fine aggregates in concrete

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ABSTRACT

The construction industry is responsible for a high consumption of natural resources, demanding high quantities of aggregate materials for use in construction. In addition, large quantities of rubber waste generated worldwide have emphasized the need to find practical reuse applications. The present study partially replaces fine aggregates by ash from a co-processing of milled and burned conveyor belt rubber waste. Test specimens prepared with ash concentrations of 0%, 5%, 10%, 15% and 20%, were used for comparing its workability, mechanical axial resistance and absorption of water by capillarity. It was concluded that the partial replacement of sand by 5% of rubber ash has improved the traditional concrete mixture, with better workability, less amount of water, leading to a greater resistance to axial compressive and acceptable absorption of water. Thus, the results confirm that the concrete with incorporation of rubber ash is a potential alternative technology to achieve sustainable development in the construction industry.

Keywords: Green concrete, Mechanical properties, Waste

RESUMO

A indústria da construção civil é responsável por um grande consumo de recursos naturais, exigindo quantidades expressivas de materiais agregados para uso na construção. Além disso, resíduos de borracha são gerados enormes quantidades em todo o mundo, enfatizando a necessidade de encontrar aplicações práticas para sua reutilização. O presente estudo substitui parcialmente agregados finos por cinzas de um co-processamento de resíduos de borracha de correias transportadoras moídas e queimadas. Amostras preparadas com concentrações de cinzas de 0%, 5%, 10%, 15% e 20%, foram utilizadas para testes de comparação de trabalhabilidade, resistência axial mecânica e absorção de água por capilaridade. Concluiu-se que a substituição parcial da areia por 5% das cinzas de borracha melhorou a mistura de concreto tradicional, com melhor trabalhabilidade, menor quantidade de água necessária, levando a uma maior resistência à compressão axial e à absorção aceitável de água. Assim, os resultados confirmam que o concreto com incorporação de cinzas de borracha é uma tecnologia alternativa potencial para alcançar o desenvolvimento sustentável na indústria da construção.

Palavras-chave: Concreto verde, Propriedades mecânicas, Resíduo

1 INTRODUCTION

Several countries currently face a shortage of natural aggregates for concrete, depending on imports to meet the demands of the construction industry. The rapid development of the market and the need for large scale infrastructure, as well as the indiscriminate exploitation of natural rocks, results in severe environmental degradation and the release of considerable amounts of dust (THOMAS *et al.*, 2018).

Seeking to combine economic viability with green alternatives, the construction industry is accepting the challenges of incorporating sustainability into production activities. The use of alternative raw materials obtained from different waste and by-products of various industries is being promoted by the concrete industry. A significant number of studies using rubber waste, in its various forms, in concrete have been carried out in the past years. However, the rubber ash form of waste as an aggregate has been the subject of very few studies (GUPTA *et al.*, 2018). Waste products can be used to save natural resources while protecting the environment from waste disposal. The use of waste ash from rubber in concrete may be an interesting solution for the disposal of this material, as it saves natural resources and could produce a more efficient material (GUPTA *et al.*, 2014).

Transportation of material by means of rubber conveyor belts is a typical transport method applied in various technological processes and is the most economical solution for the long-distance transportation of bulk materials. The conveyor belts are exposed to various impacts can be damaged and degraded. Also, its exposure to light, heat, humidity, chemicals and gaseous pollutants during their operation causes a reduction in their life, leading to the need for maintenance and replacement, generating solid waste and the need for its disposal (MARASOVÁ *et al.*, 2017; DOBROTĂ, 2013).

Rubber ash is considered as solid waste resulting from human activities through the burning of crushed rubber. In Brazil, tire waste is classified as non-hazardous non-inert Class II A, presenting metal contents (zinc and manganese) in its solubilized extract which are higher than the standards established by the Brazilian solid waste classification (BRASIL, 2004).

Aggregates are constituents that contribute about 80% of the weight and 20% of the cost of structural concrete without additives. They present a great variation in its characteristics, necessitating the study of the technology of the concrete and its quality control both before and during its use in construction (BILIM *et al.*, 2017).

Results from studies with rubber residues incorporated into the concrete indicate that the mixtures have lower density, higher hardness and ductility, and more efficient sound insulation. In addition, the unit weight of the sample containing the rubber material decreases with increasing concentration. Thus, adding rubber residues into concrete may be a potential material for use in concrete, mortar and concrete blocks, as well as being suitable for architectural applications and structural components (YILMAZ *et al.*, 2009).

Given the importance of this subject, the present study aimed to analyze the incorporation of rubber ash residues into concrete as partial replacement of the fine aggregate. The performance of traditional concrete without sand substitution was compared with the concrete mixtures prepared with different contents of rubber ash. The mechanical performance was evaluated, regarding axial compressive strength and water absorption by capillarity.

2 MATERIAL AND METHODS

2.1 Material

Commercial Portland cement (CP II Z-25) was used in this study, due to its medium rate of hardening, its suitability for most types of concrete work and its easy availability in the market, and because it follows the ASTM C150 standards (1993). Commercially available natural quartz sand (fine aggregates) and crushed gravel (coarse aggregates) were used in this study.

The rubber ash used in this study was obtained as a by-product from the co-processing of the milled and burned waste rubber in a controlled oven at a constant temperature of 500–800 °C. In the process, the rubber waste from a conveyor belt company was milled to sizes of approximately 5 x 5 x 2.5 cm and gasified in a controlled furnace boiler for later cogeneration in a reactor. The residues generated by the rubber incineration were deposited at the bottom of the boiler where they were collected and submitted to a mechanical separation process that removed the steel which was present in the rubber in its original state, leaving only the ashes of the burnt rubber used in this study.

2.2 Aggregate characterization

The mineralogical characterization regarding the structure and chemical composition of the rubber ash was evaluated by X-ray diffraction (XRD) in a Bruker AXS D8 Advance instrument (Cu Kα1,α2 radiation, 40 kV and 40 mA, in range from 5° to 80°) operating in a Bragg–Brentano θ/θ configuration was used for this purpose. The diffraction patterns were collected in a flat geometry with steps of 0.02° and accumulation time of 3 s per step. The X-ray powder diffraction data was refined following the Rietveld method with the TOPAS Academic V.5© software. The chemical composition was also determined by using Wavelength Dispersive X-ray Fluorescence (WDXRF) on a model S8 TIGER Bruker (Tokyo, Japan). The samples were analyzed in He with an X-ray source of Rh operating at 30–60 kV of voltage range, according to the measure region. The aggregates used in the concrete preparation were characterized by the particle size distribution test according to the Brazilian standard NBR 248 (ABNT, 2003).

2.3 Concrete mix proportions

The proportions of the reference mixture, made without rubber ash addition (0%), and of the mixtures made with different contents of rubber ash replacing sand, 5%, 10%, 15%, 20%, are reported in Table 1. No chemical additives were used to modify the physical properties of the concrete. The concrete mix used was calculated by the updated method of the Polytechnic School of the University of São Paulo (USP), based on the Institute of Technological Research of the State of São Paulo (IPT/EPUSP) (HELENE *et al.*, 1992). In summary, the reference mixture was predetermined to achieve the desired slump test of 11 ± 2 cm. This predetermined value for the slump, foresees a fluid concrete, as indicated by Helene *et al.* (1992) which avoids the segregation of the aggregates caused by a lack of fine materials, as the workability is not only linked to the amount of water used, but in terms of paste, also to the mortar, gravel, sand and ashes, making all elements compatible for the production of quality concrete.

The mix proportions of the mortar were fixed at 53% and the dry aggregate/cement ratio equivalent to 1:5. Thus, the sand/cement/gravel ratio was calculated (1: 2.18: 2.82) and the quantities of the concrete component materials were determined, varying only the amount of sand and rubber ash in each mix produced (Table 1).

Table 1 – Mixture proportion of concretes

Component	**Rubber ash (%)**				
	0	5	10	15	20
Cement (kg)	9.319	9.319	9.319	9.319	9.319
Sand (kg)	20.314	19.298	18.282	17.267	16.251
Gravel (kg)	26.278	26.278	26.278	26.278	26.278
Water (L)	6.060	5.990	6.650	7.250	7.850
Rubber ash (kg)	0	1.016	2.031	3.047	4.063

The mixtures were prepared in an 80 L inclined shaft concrete mixer at 28 rpm, following the addition order of: gravel, cement, rubber ash, 50% of the water, sand, the remaining water and when necessary the reducing additive of water. Shortly after mixing, the slump test was performed, prescribed by the Brazilian standard NBR NM 67 (ABNT, 1998).

Forty cylindrical specimens (100 x 200 mm) were manufactured based on the procedure for molding and curing concrete test specimens of the Brazilian standard NBR 5738 (ABNT, 2016), eight of each mixture proportion of the concretes (0%, 5%, 10%, 15% and 20%).

2.4 Concrete performance evaluation

To determine the quality of the concrete in its hardened state in relation to the mechanical performance, the axial compressive strength test of the concrete at the ages of 3, 7 and 28 days for the different ash concentrations was performed. The Instron/EMIC brand mechanical press was used with a digital controller and the methods were performed according to the Brazilian standard NBR 5739 - Compression test of cylindrical specimens (ABNT, 2018).

In addition, the water absorption by capillarity assays of the concretes manufactured with rubber ash were determined on the 28th day of curing, and performed according to the Brazilian standard NBR 9779 (ABNT, 2012). All assays were performed in duplicate.

3 RESULTS AND DISCUSSION

3.1 Aggregate characterization

The chemical composition of rubber ash depends on various factors, including the characteristics of the ash, its composition, operating conditions and so on. Therefore, XRD and WDXRF analysis were performed to determine the chemical and physical composition of the rubber ash in terms of weight percentage.

The results of the rubber ash composition analyzed by WDXRF (Table 2) revealed the compounds SiO_2, SO_3, CaO, ZnO and MgO in higher percentages. The presence of different types of oxides is due to the oxidation of the rubber at high temperatures and these compounds were expected due to the rubber characteristics and are in agreement with the data described in the literature (LIAO *et al.*, 2007). Also, the presence of SiO_2 (26.81 weight%) in mineral ash shows pozzolanic properties (AROWOJOLU *et al.*, 2019).

Table 2 – WDXRF results of rubber ash

Component	**Formula**	**Concentration (%)**
Silica	SiO_2	26.81
Sulfuric oxide	SO_3	21.27
Calcium oxide	CaO	21.00
Zinc oxide	ZnO	20.98
Magnesium oxide	MgO	5.58
Chloride	Cl^-	1.77
Iron oxide	Fe_2O_3	0.78
Potassium oxide	K_2O	0.77
Aluminum oxide	Al_2O_3	0.62
Phosphorus pentoxide	P_2O_5	0.41

The results of X-ray diffractogram of rubber ash (Fig. 1) showed an amorphous material consisting mainly of an amorphous carbon phase, with some crystalline structures, characteristic of the presence of quartz, CaO and ZnO. This data agrees with the results obtained from WDXRF.

Figure 1 – XRD patterns of rubber ash

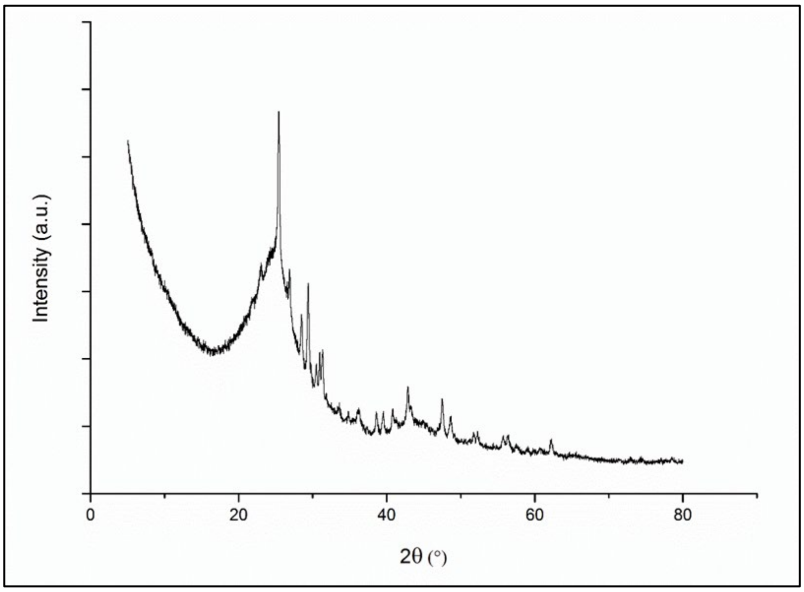
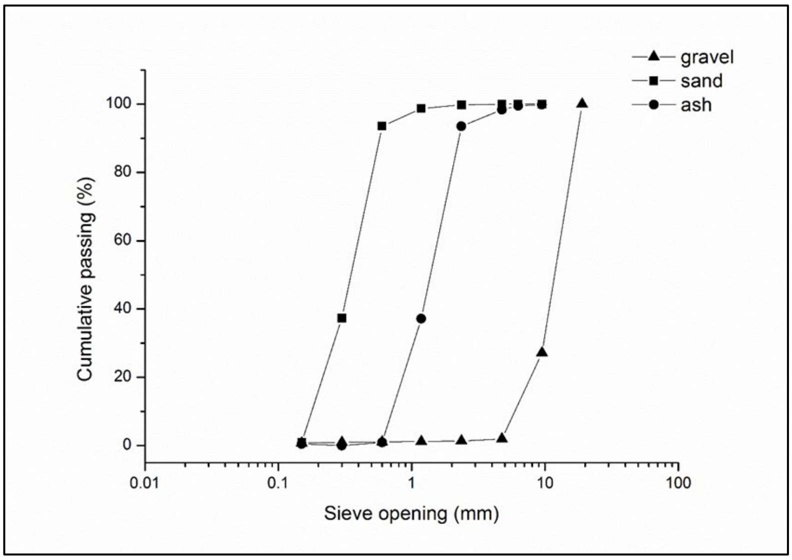


Fig. 2 shows the results of the particle size test for aggregates (gravel, sand and rubber ash). The particle size test was performed to verify the similarity of the sand with the rubber ash. It was observed that the particle size composition of rubber ash and sand were similar, even though that the sand presented smaller particle size and the majority of particles with size between 0.15 mm and 0.3 mm, while rubber ash presented particle size between 0.3 mm and 0.6 mm. Thus, it was established that the replacement of sand by rubber ash could be possible according to particle-size criteria, since they presented similar characteristics.

Figure 2 – Particle size curves for aggregates, gravel, sand and rubber ash



A set of tests were carried out in order to identify the density and water absorption of the aggregates. The results are presented in Table 3.

Table 3 – Aggregates density and water absorption

Aggregate	Density (g/cm3)	Water absorption (%)
Gravel (kg)	2.79	2.71
Sand (kg)	2.65	0.48
Rubber ash (kg)	2.38	0.30

It was observed that rubber ash presented lower density and lower water absorption when compared to sand. This may imply a lighter material, less resistant and, possibly, a mix that requires less water for its production. Similar results were observed by GUPTA *et al.* (2018).

3.2 Concrete performance evaluation

The dosing method used IPT/EUSP (HELENE *et al.*, 1992) considers the water/cement ratio the most important parameter, because besides not requiring prior knowledge of the aggregates, the procedure understands that the best mixture among the available aggregates is the one that consumes the smallest amount of water to obtain the predetermined workability.

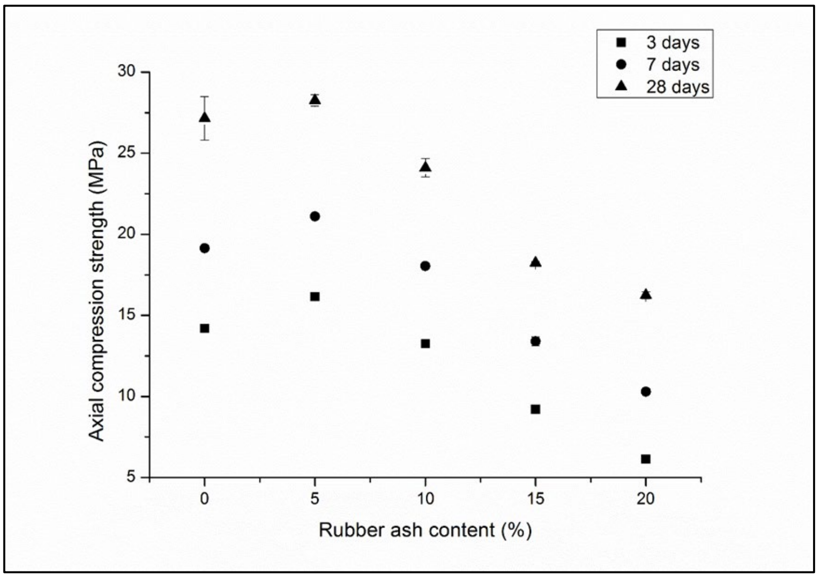
Table 1 presents the amount of water necessary for the workability and cohesion of fresh concrete to reach the predetermined value of 11 ± 2 cm measured directly with the slump test. The results showed that the greater the replacement of the fine aggregate by rubber ash, the higher the water consumption, with the exception of the 5% addition. So, with the addition of 5% of rubber ash, the desired workability was reached with a smaller amount of water in relation to the concrete without ashes, presenting a higher material performance. This may be explained by the water absorption of rubber ash being lower in comparison to sand (Table 3), and thus, when rubber ash is added in small amounts, the amount of water required can be maintained (6000 L); however, when the concentration of rubber ash added is increased, the porosity of the concrete is higher, due to its smaller density and larger size, creating voids between aggregates, requiring more water for its workability (AAMR-DAYA *et al.*, 2008).

It was noted that the workability was decreased when rubber ash was added, due to the larger amount of water used to reach the required flowability in the slump test. This is one of the main reasons that later affected the concrete in the hardened state, due to the higher porosity, its physical and mechanical performance may be lower (GUPTA *et al.*, 2014).

Knowing the particle size characteristics of the aggregates, the concrete mix proportions were calculated and concrete and molding of the specimens were prepared. They remained for 3, 7 and 28 days in the process of curing by immersion in water and finishing the faces by grinding, as established by the Brazilian standard NBR 5739 (ABNT, 2018). For each curing category and each ash concentration, two specimens were submitted to the axial compressive strength test (Fig. 3), and the results are presented in Fig. 4.

Figure 3 – Specimen submitted to the axial compressive strength test

Figure 4 – Axial compressive strength test results with 3, 7 and 28 days of curing



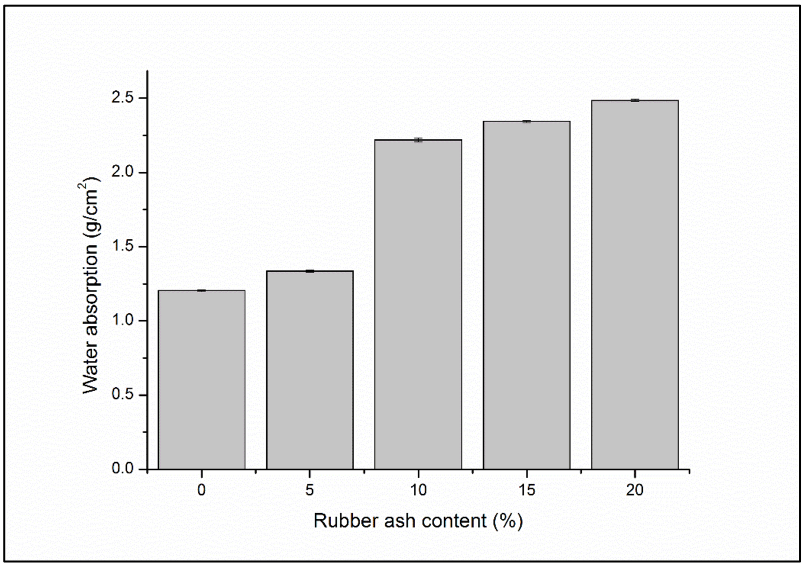
The axial compressive strength of the produced specimens was decreased with the increase of rubber ash percentage, with the exception of the concrete with 5% of rubber ash content, which presented the highest resistance of all the samples. The lower stiffness of rubber ash compared to sand may be responsible for the reduced axial compressive strength results and the high content of rubber ash makes efficient packaging difficult, forming voids in the concrete, leading to a lower axial compressive strength (AAMR-DAYA *et al.*, 2008). Gupta *et al.* (2014) and Al-Akhras *et al.* (2004) obtained similar results in their studies. The particle size of rubber ash was higher in comparison to sand (Fig. 2), also contributing to void formation in the modified concrete.

The best result for axial compressive strength for the 5% ash content may be explained by the improved and homogeneous packing promoted by the rubber ash particles, which lead to a higher workability of this mix (Table 1). Also, the composition of rubber ash may have contributed to improve the concrete characteristics, due to its high concentration of silica and calcium oxide, which are the main products of cement after hydration (AROWOJOLU *et al.*, 2019).

The performance of concrete for reducing aggressive transport and subsequent material deterioration is slightly linked to its water absorption capacity. When the concrete is in a fresh state the water is responsible for the hydration reaction of its constituent materials, forming the resistant structure of the material. In the hardened state, water can cause concrete degradation due to penetration through its pore network. The aggregate typology has a certain pore network capable of establishing a preponderant water absorption rate, because only through moisture the aggressive agents infiltrate inside the specimen (HELENE *et al.*, 1992).

To analyze the influence of water absorption by capillarity in relation to the percentage of rubber ash addition, specimens, for each selected content, aged 28 days were subjected to water absorption for 24 hours and the results are presented in Fig. 5.

Figure 5 – Water absorption by capillarity for specimens aged 28 days for 24 hours



The water absorption capacity of the concrete is influenced by the porosity of the matrix and/or the residue itself. It was shown that the rubber content has affected the porosity of the concrete, thus, affecting the water capacity results. The higher the concentration of rubber ash, the higher the water absorption of the concrete. The water absorption of rubber ash concrete was 2.48 g/cm² for 20% replacement, while for 0% replacement it was 1.21 g/cm², which corresponds to more than twice the water absorption. This result is explained due to less efficient compaction of the modified concrete due to the lower rubber ash density, as presented in Table 3 (GUPTA *et al.*, 2014).

4 CONCLUSIONS

It was concluded that the use of rubber ash in concrete with concentrations of 5% and 10% is feasible. The addition of 5% of rubber ash improved the traditional concrete mixture, producing better workability with a lower amount of water, leading to a greater compressive strength and acceptable water-absorption rate. Thus, the results confirm that the concrete with incorporation of rubber ash as a partial replacement of fine aggregates is a potential alternative technology to achieve sustainable development in the construction industry, converting a residue of unserviceable rubber ash into an addictive of concrete for achieving better characteristics and promoting the saving of natural resources.

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